BEFORE THE ENVIRONMENT COURT
AT WELLINGTON

ENV-2015-WLG-024

IN THE MATTER	of the Resource Management Act 1991
AND	
IN THE MATTER	of applications for resource consent by Site 10 Redevelopment Limited Partnership and Wellington City Council in respect of the area known as Site 10

STATEMENT OF EVIDENCE OF DR MICHAEL JOHN REVELL ON BEHALF OF SITE 10 REDEVELOPMENT LIMITED PARTNERSHIP AND WELLINGTON CITY COUNCIL
3 JULY 2015

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INTRODUCTION

1. My full name is Dr Michael John Revell. I am a meteorologist, and currently principal scientist and group manager of meteorology and remote sensing at the National Institute of Water and Atmospheric Research Limited (**NIWA**)

2. I graduated with a Bachelor of Science (Honours) degree in Mathematics from Canterbury University in 1974. I also completed a PhD in meteorology at Reading University in the United Kingdom in 1982 investigating how mountains affect weather systems.

3. After graduating from Canterbury University, I was employed for 16 years at the New Zealand MetService before joining NIWA in 1992 where I have worked as an atmospheric scientist ever since.

4. I have over 32 years' experience in the weather business. My expertise includes assessing how the weather affects our daily activities, including providing estimates of extreme weather conditions that structures will have to withstand in order to meet New Zealand building codes. During this time, I have developed and used weather models so I have a good understanding of the science that goes into them and their limitations.

5. I have been engaged by the applicants to provide expert witness evidence in respect of the development at the Kumutoto site at 10 Waterloo Quay.

CODE OF CONDUCT

6. I confirm that I have read the Code of Conduct for Expert Witnesses contained in the Environment Court Practice Note 2014 and that I agree to comply with it. I confirm that I have considered all the material facts that I am aware of that might alter or detract from the opinions that I express, and that other than where I state that I am relying on the evidence of another person, my evidence is within my area of expertise.

BACKGROUND AND SCOPE OF EVIDENCE

7. I have been asked to provide evidence in relation to expected sea level variation and effect of waves on the Kumutoto site over the next 100 years.

8. I was also involved in providing evidence on similar issues for the Environment Court hearing for the redevelopment of the Overseas Passenger Terminal in 2008.

9. The key issues are:

(a) the current mean sea level relative to chart datum and which sea level has been used in the various reports submitted and referred to;

(b) the expected change in the mean sea level due to climate change over the next 100 years;

(c) maximum expected sea level height at the Kumutoto Site due to the joint action of sea level height (tides, storm surge, inverse barometer effect, etc) and wave action including propagation from open water into the shore.

10. In the process of forming my views, I will rely on several key documents: *Sea level variability and trends: Wellington Region*, prepared for Greater Wellington Regional Council by Dr Rob Bell of NIWA in 2012; The Intergovernmental Panel on Climate Change (**IPCC**) *Fifth Assessment Report, Climate Change 2013* (**IPCC 2013**); and *A Guidance Manual for Local Government in New Zealand* (MfE, 2008) (**MfE 2008**).

11. My evidence will cover the following matters:

(a) A brief description of NIWA;

(b) Extreme sea levels, sea-level variation and base level of the sea;

(c) Historical sea-level rise in New Zealand;

(d) Sea level rise due to climate change;

(e) Latest IPCC global sea-level temperature rise projections;

(f) Application of latest projections to New Zealand;

(g) Joint probabilities of sea level height and wave action;

(h) Calculations by NIWA scientists of the maximum expected sea level height at the Kumutoto Site due to the joint action of sea level height (tides, storm surge, inverse barometer effect etc) and wave action including propagation from open water into the shore; and

(i) Comments on submissions.

EXECUTIVE SUMMARY

12. I have been asked to provide evidence in relation to expected sea level variation and effect of waves on the Kumutoto site over the next 100 years. Staff at NIWA have revised estimates of joint probabilities of storm wave heights and sea levels, specifically for the Queens Wharf frontage of the proposed development. The results of this work can be summarised as follows:

(a) All assessments for planning and decision timeframes out to 2015 should consider the consequences of a mean sea-level rise of 1 m relative to the present-day mean sea level. Present-day mean sea level is 0.208 m relative to the Wellington Vertical Datum 1953 (**WVD-53**). For planning and decision timeframes beyond 2015, an allowance for sea-level rise of 10 mm per year beyond 2015 is recommended (in addition to the above recommendation).

(b) A revised extreme sea level analysis of water levels at Queen’s Wharf indicates there is a 0.01 annual exceedance probability (**AEP**) that a storm tide will reach 1.35 m above WVD-53 for all but wave and climate change effects.

(c) Combinations of sea level and wave height (including the guidance for sea level rise (1.0 m by 2115) and the effect of expected changes (20% increase of wind speed) to regional wind patterns over New Zealand), with specified joint annual exceedance probabilities of 0.01 are given in columns 4 and 7 respectively of Table 2-10 of **Appendix 1** in this evidence.

(d) When a simple estimate of runup associated with each value of significant wave height in the joint exceedance table 2-10 is included, for 2115 conditions (1 m sea level rise and 20% wind increase) at site 16 (the most appropriate for the proposed development) the maximum sea level plus runup for a 0.01 AEP event is 2.41 m above WVD-53.

(e) This level is above most of the existing shore protection but below the proposed ground floor level of the building at Site 10. Therefore, including the guidance for sea level rise (1.0 m by 2115), a 0.01 AEP event by the year 2115 would overtop the existing shore protection but not enter the building.

A BRIEF DESCRIPTION OF NIWA

13. NIWA was established in 1992 as a Crown Research Institute. It operates as a standalone company with its own board of directors. Shares are held by the Crown.

14. NIWA's mission is to provide a sound scientific basis for the sustainable management and development of New Zealand's natural resources.

15. In particular, NIWA undertakes climate monitoring and prediction, and identifies weather related hazards including sea level variation due to tidal, storm and wave effects and climate change. NIWA provides the technical information government agencies rely upon to develop their building planning policies.

EXTREME SEA LEVELS, SEA-LEVEL VARIATION AND BASE LEVEL OF THE SEA

16. Sea levels are important along the Wellington Harbour coastline for two primary reasons: the tidal height governs the likelihood of coastal inundation, especially when combined with storm surge; and sea-level also sets the base level for wave attack at the coastline and hence is an important factor in determining the magnitude of wave overtopping of seawall structures, and the potential for damage to nearby buildings.

17. I will separate the discussion of sea level variation into two components (assumed to be independent): that due to climate change and that due to the joint effects of tides, storm surge and wave action.

18. The discussion below of expected sea level variation due to climate change is based on MfE 2008 together with an updated assessment of the science of climate change by Working Group I in IPCC 2013 (IPCC 2013).

19. For the expected sea level variation due to tides, storm surge and wave action, I will also refer to **Appendix 1** of my evidence. **Appendix 1** presents results from a study by NIWA scientists Richard Gorman, Glen Reeve and Scott Stephens, commissioned by Willis Bond to revisit NIWA's previous 2006 and 2009 reports on Wellington harbour wave climate to provide revised estimates of joint probabilities of storm wave heights and sea levels, specifically for the Queens Wharf frontage of the proposed development. I support and rely on the results of the study.

20. The baseline for the IPCC projections from the recent (2013) 5th Assessment Report of Working Group I (IPCC 2013) is also used in various NIWA reports on sea level rise. The baseline is the average Mean Sea Level (**MSL**) for the two decades 1986 to 2005, which sets the zero for the future projections as 0.17 m above WVD-53.

21. In other words, the recommended allowance for sea level change by the IPCC in IPCC 2013 and in MfE 2008 should have 0.17 m added to it to give the change relative to WVD-53. In this evidence, since it is now 2015, I have chosen to add 0.208 m to give the change relative to WVD-53 as that is the difference between WVD-53 and MSL for the last decade as indicated in Table 2-7 of **Appendix 1** to my evidence.

Historical sea-level rise in New Zealand

22. The analysis of sea-level rise NIWA scientists have undertaken around New Zealand indicates that New Zealand's relative sea-level rise rates are similar to global average rates of rise.

23. Historically up to the near-present (2008), the average rate of relative sea-level rise since the early 1900s has been 1.7 ±0.1 mm/year across New Zealand (Hannah & Bell, 2012). The absolute rate of sea-level rise across New Zealand is approximately 2.0 mm/year once an average long-term uplift due to Glacial Isostatic Adjustment (sometimes called continental rebound - the rise of land masses that were depressed by the huge weight of ice sheets during the last

glacial period) has been applied, although there will be local variations in vertical land movement.

24. This New Zealand average rate of rise fits reasonably well with global-average sea-level change over the 20th century of 1.7 ±0.3 mm/year (Church & White, 2006; Bindoff et al. 2007). This close match means global-average projections with an adjustment for any NZ-wide departures from the global average can be applied to New Zealand regions, until such time that local monitoring of relative sea-level rise shows otherwise.

Sea level rise due to climate change

25. In MfE 2008, two sea-level rise values were provided as tie-points when considering a range of possible sea-level rises in a hazard-risk assessment. These tie-point values were provided to start the risk assessment with a rise of 0.5 m by the 2090s (2090–2099) relative to a 1990 average baseline and at the very least consider at least a 0.8 m rise by the 2090s.

26. Adopting a planning timeframe for at least the next 100 years as required by the New Zealand Coastal Policy Statement (**NZCPS**) (Hazard Policies 24, 25 and 27), now out to 2115, means the equivalent sea-level rise tie-points for the risk assessment approach in MfE 2008 change from 0.5 m and 0.8 m by the 2090s to 0.7 m and 1.0 m by 2115, relative to the same 1990 baseline and assuming the extrapolation of a steady acceleration in sea-level rise based on the intermediate sea-level rise values for each decade in Table 2.3 of MfE 2008.

Latest IPCC global sea-level rise projections

27. In September 2013, the IPCC's Working Group I[1] released IPCC 2013. The projections for global-average sea-level rise out to 2100 are shown in **Figure 1** based on Figure SPM.9 from the Summary for Policymakers.

28. **Figure 1** shows the median estimate and the assessed likely ranges of sea-level rise focusing on two representative concentration pathway (**RCP**) scenarios, RCP2.6 and RCP8.5. The RCPs are emission pathways with starting values and estimated emissions up to 2100, based on assumptions

1 Working Group I covers the scientific basis, while Working Group II and III cover adaptation and mitigation respectively - their Assessment Reports were released in April 2014.

about economic activity, energy sources, population growth and other socio-economic factors.

29. The RCP2.6 scenario assumes very low greenhouse gas concentration levels by 2100, and in order to be achieved requires quick implementation of severe curbs on emissions petering out to zero emissions by the end of this century. RCP2.6 is known as a “peak-and-decline” scenario, with global average temperatures (actually - global combined land and ocean annually-averaged surface temperatures) likely to be held just under 2°C by 2100.

30. RCP8.5 is a business-as-usual scenario based on present levels of greenhouse gas emissions, but including some growth in emissions from economic and population growth. This business-as-usual scenario, which is more likely to eventuate than the RCP2.6, is likely to result in a global average temperature rise in the range of 3-5°C by 2100.

Application of latest projections to New Zealand

31. The two tie-points from MfE 2008 that apply to the mid-2090s are annotated on the latest IPCC sea-level rise projections for RCP2.6 and RCP8.5 in **Figure 1**. These tie-point values include a 0.05 m additional sea-level rise by the 2090s in the NZ-wide region over and above the global average projections, which has since been confirmed by a more detailed study of the NZ-regional sea-level response by Ackerley et al. (2013).

32. Taking this regional increase into account, the MfE 2008 tie-points sit well with the latest global-mean sea-level rise projections from IPCC 2013. The low-emission RCP2.6 scenario is unlikely to be achieved, unless severe curbs on emissions are quickly agreed to globally, so the lower band of sea-level projections are likely to be exceeded by 2100.

33. The last three IPCC assessments in 2013, 2007 and 2001 have produced reasonably consistent projections for the end of the 21st century, on the back of a large increase in research papers and modelling effort on the topic in the last 5 years. This provides more confidence in interpolating the IPCC global-average sea-level rise projections to the local level.

34. Higher sea-level rises by 2100 than those shown in **Figure 1** cannot be ruled out. Based on current understanding, only the collapse of marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean sea level to rise substantially above the likely range of projections during the 21st century (IPCC, 2013). However, there is medium confidence by IPCC 2013 that this additional contribution would not exceed several decimetres of sea level rise during the 21st century. Because the science is not yet settled on this issue and it is not yet possible to set reliable probabilities for associated sea level changes, I have not considered this additional possibility in the 1% joint AEP levels for Queens Wharf.

35. **Figure 2** repeats **Figure 1**, but also extends the MfE 2008 tie-points out to 2115 to provide estimates out to at least 100 years as required by the NZ Coastal Policy Statement (Hazard Policies 24, 25 and 27). I have set these two tie-points to 0.7 and 1.0 m by 2115, which is documented in Britton et al. (2011). These extended values to 2115 still sit comfortably with the trends in the higher RCP scenarios as shown in **Figure 2**.

[see over page]

Sea-level rise (global mean)

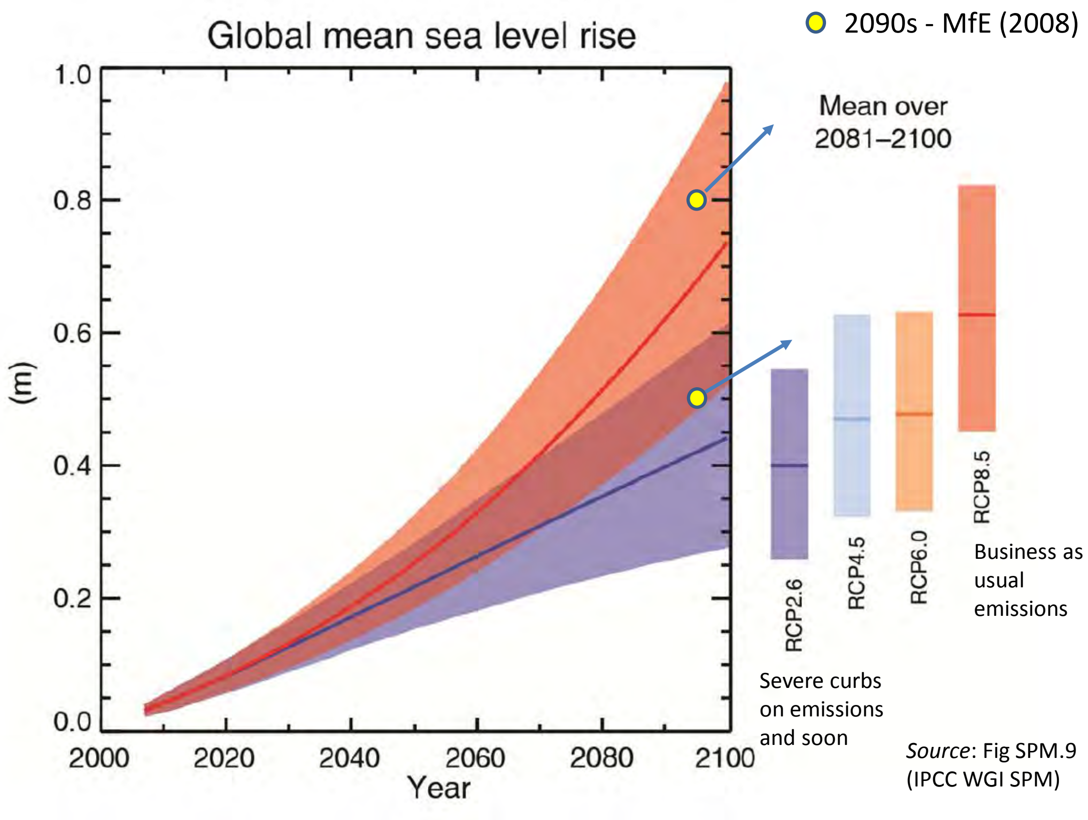

Figure 1: Projections of global mean sea-level rise over the 21st century relative to the 1986-2005 baseline from ensembles of climate-ocean models for the RCP2.6 (blue–severe curbs on emissions) and RCP8.5 (brown–business-as-usual) scenarios. The heavy line is the median estimate and the shading represents the assessed likely range.

The yellow dots represent the tie-point sea-level rises to consider in a hazard-risk assessment of 0.5 m and at least 0.8 m by the mid 2090s contained in MfE, 2008. (*Source of background graphic:* IPCC 2013)

Sea-level rise (global mean) – 2115

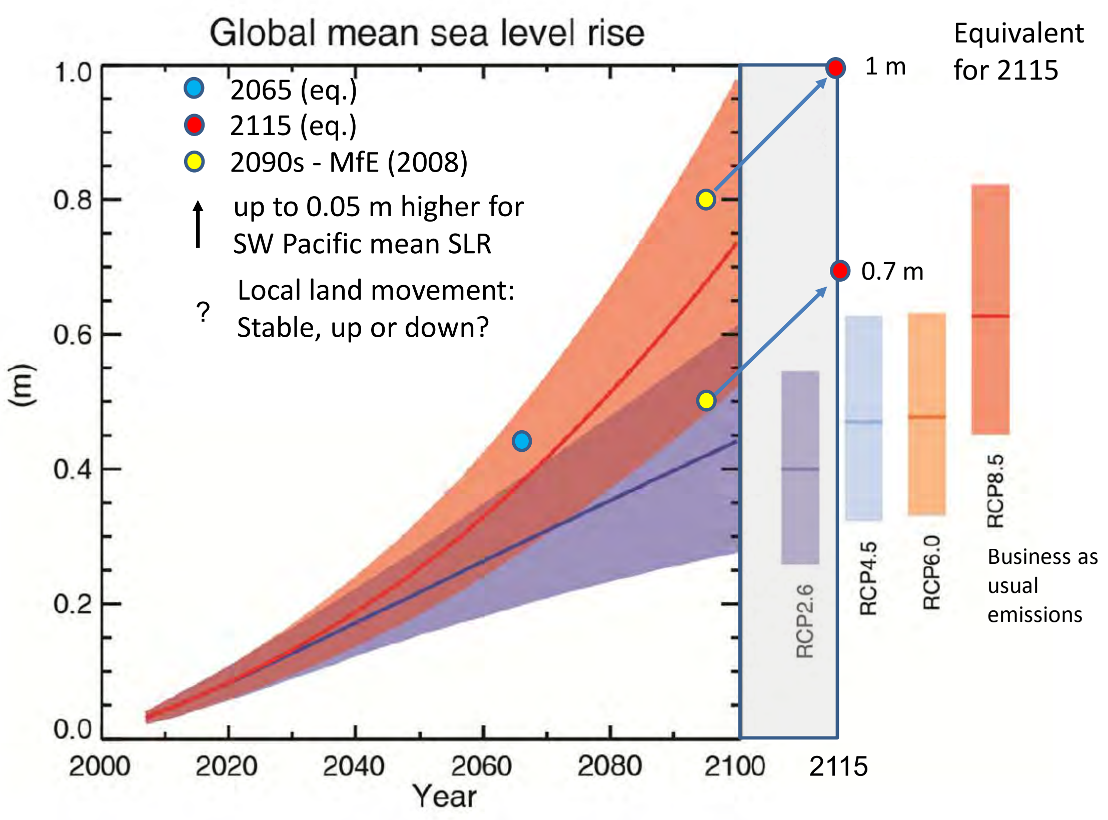

Figure 2: Projections of global mean sea-level rise over the 21st century relative to the 1986-2005 baseline from ensembles of climate-ocean models for the RCP2.6 (blue–severe curbs on emissions) and RCP8.5 (brown–business-as-usual) scenarios.

The yellow dots represent the tie-point sea-level rises to consider in a hazard-risk assessment of 0.5 m and at least 0.8 m by the mid–2090s contained in the local government guidance manual (MfE, 2008) and the red dots are the recommended extensions through to 2115 of 0.7 m and 1.0 m and the blue dot is 0.45 m by 2065 (equivalent trajectory to 0.8 m by 2095). Sea-level rise for the NZ-wide region is likely to be up to 0.05 m higher than the global mean, which is built into the MfE (2008) guidance. [*Source of background graphic:* IPCC (2013)]

36. In summary, all assessments for planning and decision timeframes out to 2015 should thus consider the consequences of a mean sea-level rise of 1 m relative to the present-day mean sea level. Present-day mean sea level is 0.208 m relative to WVD-53. For planning and decision timeframes beyond 2015 an allowance for sea-level rise of 10 mm per year beyond 2015 is recommended (in addition to the above recommendation).This value will be referred to in the calculations in the next section.

Joint probabilities of sea level height and wave action

37. The main component of sea level variation is the astronomical tide but sea level at any location can be elevated (or lowered) due to:

(a) climatic fluctuations operating over annual to decadal timescales (for example the 2 – 4 year El Niño Southern Oscillation and the 20-30 year Interdecadal Pacific Oscillation);

(b) storm surge due to atmospheric pressure and wind effects; and

(c) wave action, set-up and run-up at the shoreline.

38. Damage to waterfront infrastructure may be caused by a combination of hazard variables, for example high sea-levels and large waves. However, it is not necessarily the case that the higher an extreme event for a particular single variable, e.g. sea-level, the higher the level of damage. Often combinations of two or more hazard variables of moderate severity can cause more damage than an extreme event from a single variable.

39. When considering waterfront inundation, overtopping, or the design or hydraulic performance of waterfront structures, we are interested in determining not only the probability of occurrence of individual hazard variables, but also the probability of the joint-occurrence (or joint probability) of a combination of variables – in this case high sea levels and big waves.

40. In the case of water levels and wave conditions, if a certain water level always occurs at the same time as a given wave height, then the two variables are completely dependent. Alternatively, if they are completely independent, then there is no correlation between them. In reality, the assumption of complete independence would usually lead to underestimation of the joint probability recurrence interval[2] with complete dependence being too conservative.

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2 The recurrence interval (or return period) can be defined as the average time interval, usually in years, between the occurrence of a high storm tide (or other coastal hazard event such as wave height) of a given magnitude or larger. An alternative representation is the Annual Exceedance Probability, i.e. the probability (chance) of occurrence, in any year, of a storm tide equalling or exceeding a specified magnitude. For large return periods, the AEP is the reciprocal, or inverse, of the recurrence interval. For example, a flood that would be equalled or exceeded on the average of once in 100 years would have a recurrence interval of 100 years and a 0.01 probability, or 1 percent chance of occurring or being exceeded in any year.

41. The correlation between waves and water levels will usually lie between the two extremes of complete dependence and complete independence. This is due to two main reasons. First, certain weather conditions, such as the tracking of extra-tropical cyclones or low pressure systems close to New Zealand's coast, will potentially produce both high wave conditions and high storm surge. However, as storm surge in New Zealand is relatively moderate compared to the astronomical component of water level (which is completely independent of meteorological conditions), such correlation may not be that high.

42. The second reason is due to the depth-limiting effect that water level has on wave conditions in shallow water. In such a case, there may well be a high correlation between high water level and wave conditions. This is particularly important in the context of future sea level rise, in that increasing sea-levels will also result in higher wave conditions at a particular location (all other things being equal).

43. In the New Zealand context, the design of waterfront structures, or the setting of minimum floor elevations, has traditionally been conducted with a poor knowledge of how these different hazard variables are correlated, e.g., assuming that extreme water levels occur at the same time as extreme wave conditions, potentially leading to design over-estimates and associated cost implications.

44. To objectively calculate joint probabilities requires accurate data for the marginal probabilities of each of the individual variables. The two marginal variables must be matched in time, with a minimum record length of about 4 years and preferably 10 or more.

45. Once high-quality datasets are assembled and matched, statistical distributions are fitted to the extreme values of the hazard variables. This gives an indication of the return probabilities of extreme values of the hazard variables by themselves. Based on the overlapping wave and water level datasets, the dependence between the extreme values of the variables can be derived, and the joint probabilities calculated based on this dependence.

46. This type of analysis was conducted by NIWA in March 2006 for the Wellington Harbour frontage for Wellington City Council as part of a wider study (**Gorman**

et al. 2006) assessing the potential impacts of climate change on weather and coastal hazards for Wellington City.

47. The wave component of this study in Wellington Harbour used the SWAN ("Simulating WAves Nearshore") model (Booij, Ris et al. 1999; Ris, Holthuijsen et al. 1999) to derive wave climate at a set of output locations offshore within the harbour.

48. SWAN is able to represent all of the processes that determine wave climate to some extent, but in the case of reflection and diffraction, this capability is only limited. In Gorman et al. 2006, this was not a significant limitation due to the distance offshore of the selected output sites. But both reflection and diffraction will be important processes which need to be addressed in the immediate vicinity of the wharves, in particular at Site 10 on Waterloo Quay.

49. Proper representation of reflection and diffraction requires a high-resolution phase-resolving model, of which several are available globally. NIWA selected the ARTEMIS[3] model (Aelbrecht 1997), which is part of the widely-applied TELEMAC–MASCARET modelling system developed by Laboratoire National d'Hydraulique (Electricite de France).

50. Conversely, ARTEMIS does not compute the growth of waves subject to wind action. Hence NIWA combined the two models, using SWAN to compute wave growth across Wellington Harbour, then applying those results at the offshore boundary of an ARTEMIS simulation which computes the resulting wave patterns near the waterfront. This work is described in detail in **Appendix 1** of my evidence.

51. The sites in the region of interest at which these significant wave height calculations were done are numbered 1 to 24 and displayed in Figure 2-3 of **Appendix 1** of my evidence. The ARTEMIS output sites can be grouped into two sets: more exposed outer sites (1, and 3-11), and more sheltered sites (2, and 12-24) in the Queen's Wharf area.

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3 Agitation and Refraction with Telemac on a MildSlope
http://www.opentelemac.org/index.php/presentation?id=19

52. The rightmost column of Table 2-5 in **Appendix 1** of my evidence shows the 0.01 AEP storm peak significant wave height at ARTEMIS output sites under present day climate conditions.

53. For the outer sites, 0.01 AEP peak wave heights range from 1.61 – 2.08 m, while the Queen's Wharf group have 0.01 AEP values less than 1 m, with some considerably less depending on their degree of protection by local wharf structures: for example sites 15, 16 and 17 along the Kumutoto Wharf have 0.01 AEP values of 0.29 m, 0.18 m and 0.05 m, respectively.

54. The site most likely to be appropriate for determining what will happen at the Kumutoto is site 16 where the 0.01 AEP storm peak significant wave height is 0.18 m.

55. In the process of establishing likely sea levels to be expected over the next 100 years, NIWA also performed a revised extreme sea level analysis and this is described in section 2.6 and displayed in Figure 2-6 of **Appendix 1** of my evidence. This analysis indicates maximum sea level variation for a 0.01 AEP event of 1.35 m above WVD-53 for all but wave and climate change effects, as can be seen in column 4 of table 2-8 of **Appendix** 1.

56. As described in **Appendix 1**, the combinations of sea level and wave height can be calculated at a subset of these ARTEMIS output sites, with specified joint annual exceedance probabilities. Calculation of these probability distributions includes the guidance for sea level rise (1.0 m by 2115) and the effect of expected changes (20% increase of wind speed) to regional wind patterns over New Zealand. The corresponding sea level above WVD-53 and wave height at site 16 with an AEP of 0.01 are given in columns 4 and 7 respectively of Table 2-10 of **Appendix 1** of my evidence.

57. Despite these different variable combinations all having the same joint probability of occurrence, generally a particular combination will provide the worst case for overtopping or structural damage to a coastal structure.

58. In order to illustrate this, as explained in section 2.8 of **Appendix 1**, NIWA estimated the effect of runup by applying an empirical formulae from the Eurotop manual (Pullen, Allsop et al. 2007).

59. Inspection of a set of nearshore bathymetry transects through the Queens Wharf area, indicated a bottom slope of 0.5 was appropriate and other required constants were selected as described in section 2.8 of **Appendix 1** of my evidence. The runup associated with each value of significant wave height was calculated and the results are shown in the joint exceedance Table 2-10. For site 16, the results are given in column 6 of Table 2-13 of **Appendix 1**. For 2115 conditions (1m sea level rise and 20% wind increase) at site 16 the maximum sea level plus runup for a 0.01 AEP event is 2.41 m above WVD-53.

60. I note that, given the sheltered location, the highest total levels are predominantly associated with high (still-water) sea levels, rather than larger waves on top of lower still-water levels. It should be stressed that the simple runup estimate made here is only indicative of the total hazard associated with a given combination of waves and sea level for the specific shore shape specified and engineers should do their own calculations for whatever shore protections and structures are actually put in place using the combinations of sea level and waves from Table 2-10 in **Appendix 1**.

SUBMISSIONS

61. The following submissions raised issues about sea level rise, storm surges and extreme weather events:

Submitter Name	Submitter Number
Waterfront Watch	10
Pauline and Athol Swann	13
Chris Greenwood	14
Chris Horne and Barbara Mitcalfe	26
The Architectural Centre	27
Catherine Underwood	45

62. In essence the common theme in these submissions was that sea level rise, storm surges and extreme weather events should be taken into account for this development. In my opinion this is exactly what the analysis contained in **Appendix 1** of this evidence does.

SECTION 87F REPORT

63. I have read the section 87F report prepared for this matter by the Wellington City Council. The matters raised in the report by Greater Wellington Regional Council will be addressed by other witnesses.

64. I have the following comments on paragraphs 130 and 131 of the report.

65. Further calculations by NIWA staff, commissioned by the applicant, which include extreme water levels, climate change driven sea level rise, wave propagation and attenuation and indicative wave runup at the shore edge, assess the total inundation level to be 2.41 m above WVD-53 for the proposed development for a 0.01 AEP event by 2115.

66. The 0.2 m tidal fluctuations referred to in the Reinen-Hamill report are already included in NIWA's latest extreme value analysis of water levels at Queen's Wharf, and the Dawe report has double counted the 0.208 m allowance for current sea levels above WVD-53, and the extra windiness expected by 2115 mostly affects waves, which are very small at the proposed development site, not sea levels.

67. I also note in respect of Dr Iain Dawe's memorandum at Annexure 10 of the report that the latest extreme sea level analysis by NIWA staff indicates the present day 0.01 AEP storm tide to be 1.35 m above WVD-53, excluding any wave effects (this already includes a 0.208 m allowance for current sea levels above WVD-53).

68. Latest NIWA calculations indicate, taking into account a further sea level rise of 1.0 m and potential increased intensity of storm events, a 0.01 AEP event in 100 years could reach elevations above WVD-53 of 2.41 m, including wave activity and an indicative wave runup at the shoreline near the proposed development – site 16 in NIWA's report.

69. In essence, Dr Dawe's report has in my view double counted the 0.208 m allowance for current sea levels above WVD-53, and the extra windiness expected by 2115 mostly affects waves, which are very small at the proposed development site, not sea levels.

CONCLUSIONS

70. In summary, all assessments for planning and decision timeframes out to 2015 should consider the consequences of a mean sea-level rise of 1 m relative to the present-day mean sea level. Present-day mean sea level is 0.208 m relative to WVD-53. For planning and decision timeframes beyond 2015, an allowance for sea-level rise of 10 mm per year beyond 2015 is recommended (in addition to the above recommendation).

71. A revised extreme sea level analysis of water levels at Queen's Wharf indicates there is a 0.01 annual exceedance probability that a storm tide will reach 1.35 m above WVD-53 for all but wave and climate change effects.

72. Combinations of sea level and wave height (including the guidance for sea level rise (1.0 m by 2115) and the effect of expected changes (20% increase of wind speed to regional wind patterns over New Zealand), with specified joint annual exceedance probabilities of 0.01 are given in columns 4 and 7 respectively of Table 2-10 of **Appendix 1**.

73. When a simple estimate of runup associated with each value of significant wave height in the joint exceedance Table 2-10 is included, for 2115 conditions (1 m sea level rise and 20% wind increase) at site 16 (the most appropriate for the proposed development) the maximum sea level plus runup for a 0.01 AEP event is 2.41 m above WVD-53.

74. I note that this level is above most of the existing shore protection but below the proposed ground floor level of the building at Site 10. Therefore, including the guidance for sea level rise (1.0 m by 2115), a 0.01 AEP event by the year 2115 would overtop the existing shore protection but not enter the building.

Michael John Revell
3 July 2015

Appendix 1: NIWA wave climate calculations for Queen’s Wharf

1 Background

Willis, Bond and Co. Ltd has requested that NIWA provide advice on wave conditions at the Kumutoto development site at 10 Waterloo Quay, Wellington.

To that end, a study was commissioned to revisit NIWA's previous 2006 and 2009 reports on Wellington harbour wave climate to provide revised estimates of joint probabilities of storm wave heights and sea levels, specifically for the Queens Wharf frontage of the proposed development.

The 2006 study produced extreme statistics for a set of locations off the harbour coast, of which "site 6" was the closest to Queens Wharf. The SWAN (“Simulating WAves Nearshore”) model (Booij, Ris et al. 1999; Ris, Holthuijsen et al. 1999) used represented the growth and transformation of wind-generated waves across the harbour to these locations, but did not account for changes in wave conditions further shoreward due to shoaling, refraction, reflection and diffraction associated with the detailed shape of the waterfront and nearshore bathymetry.

The stated aims of the present study are to:

1. Identify from the 2006 and 2009 studies a set of (approximately 40) historic events producing the highest impact in terms of combined wave height and sea level at site 6, as tabulated in Table 1 of the 2009 report
2. Rerun the SWAN wave generation model used in the 2006 study, but this time for detailed simulations of those events.
3. Apply a phase-resolving nearshore wave model (ARTEMIS), to take wave conditions predicted by these SWAN simulations right into the shore. This model will provide a more accurate representation of diffraction and reflection than is possible with SWAN.
4. This will provide a mapping from "site 6" wave heights to wave heights at the wharf, which can be used to adjust previous estimates of joint probabilities to apply at the Queens Wharf waterfront.
5. Adjustments will also be made to account for up-to-date projections of future sea level rise.

In relation to the final point, we note that the New Zealand Coastal Policy Statement (NZCPS) mandates that planning timeframes of “at least 100 years” from present should be considered, i.e. we need to consider timeframes to 2115 and beyond. The present guidance, Ministry for the Environment (2008), considers that, at a 100 year timescale, sea level rise of 1.0 m should be included. Hence we shall consider sea level rises of 0.5 m and 1.0 m, for 50-year and 100-year timescales, respectively.

On the other hand, the 2006 study (Gorman, Mullan et al. 2006) considered climate change scenarios for 2050 and 2100, assuming respective sea level rises of 0.15 m and 0.40 m, respectively, along with respective increases in wind speed of 10% and 20%. As far as the direct effect on wave conditions is concerned, the changes in wind speed (which act over the full fetch across Wellington Harbour) can be expected to have more impact than the changes in sea level (which have an impact only through changes in shallow-water processes such as bed friction). In the absence of any more advanced guidance on expected wind regimes for Wellington, we therefore consider the changes in wave climate considered in the 2006 study to be relevant to 50 and 100 year projections from the present day, as long as they are considered in conjunction with respective 0.5 m and 1.0 m changes in sea level.

2 Wave modelling methods and results

The wave climate in the immediate vicinity of Queen's Wharf is a result of the following processes:

1. Wind input – the transfer of energy to growing waves from winds blowing over the extent of Wellington Harbour (the wharf area is not exposed to waves generated outside the harbour entrance)
2. Deep water wave breaking – the dissipation of wave energy through whitecapping
3. Nonlinear interactions – the transfer of energy between waves of different frequencies and propagation directions
4. Refraction – process by which the direction of a wave moving in shallow water at an angle to the seabed contours is changed (e.g., the part of the wave in shallower water moves more slowly than the part still advancing in deeper water).
5. Nearshore wave breaking – depth-induced steepening and eventual breaking of waves as they shoal into shallower water, and depends on the wave period how offshore they break e.g., swell waves feel the bottom in greater depths than wind sea.
6. Diffraction – where wave energy is transmitted laterally along a wave crest. When part of a train of waves is interrupted by a barrier such as a rock revetment or breakwater of a comparable physical scale to the wave length. Diffraction is the "spreading" of waves into the sheltered region within the barrier's geometric shadow.
7. Reflection– part of an incident wave that is returned seaward when a wave impinges on a steep beach, rocky outcrop, rock revetment or other reflecting structure. Porous multi-layer rock armour layers and akmons provide substantial absorption of wave energy, thereby reducing reflection, which is controlled in models by a reflection coefficient.

A previous study (Gorman, Mullan et al. 2006) of wave climate in Wellington Harbour used the SWAN model to derive wave climate at a set of output locations offshore within the harbour. SWAN is able to represent all of the processes listed above to some extent, but in the case of reflection and diffraction this capability is only limited. In the 2006 study this was not a significant limitation due to the distance offshore of the selected output sites. But both reflection and diffraction will be important processes in the immediate vicinity of the wharves, as is now required to be addressed.

Proper representation of reflection and diffraction requires a high-resolution phase-resolving model, of which several are available globally. NIWA selected the ARTEMIS[4] model (Aelbrecht 1997), which is part of the widely-applied TELEMAC–MASCARET modelling system developed by Laboratoire National d'Hydraulique (Electricite de France).

Conversely, ARTEMIS does not compute the growth of waves subject to wind action (controlled by the first three processes listed above). Hence we combined the two models, using SWAN to compute wave growth across Wellington Harbour, then applying those results at the offshore boundary of an ARTEMIS simulation which computes the resulting wave patterns near the waterfront.

2.1 The SWAN spectral wave generation model

The SWAN model (Booij, Ris et al. 1999; Ris, Holthuijsen et al. 1999) is a spectral wave model intended for shallow water applications in coastal and estuarine environments. It computes the evolution of the wave energy spectrum in position (*x, y*) and time (*t*), explicitly taking into account the various physical processes acting on waves in shallow water. These include the effects of refraction by currents and bottom variation, and the processes of wind generation, white-capping, bottom friction, quadruplet wave-wave interactions, triad wave-wave interactions and depth-induced breaking. The model can incorporate boundary conditions representing waves arriving from outside the model domain.

The SWAN model is based on representing a statistical description of sea state in terms of the wave energy spectrum. In general, the sea surface elevation $\eta(x,y,t)$ at position coordinates *x* and *y*, and time *t*, can be represented as a sum of sinusoidal waves:

$$\eta(x,y,t) = \sum_{m=1}^{M} A_m \cos[k_m(x\cos\theta_m + y\sin\theta_m) - \sigma_m t + \psi_m] \tag{1}$$

with various values of amplitude A_m, wavenumber k_m, frequency $\sigma_m = 2\pi f_m$, propagation direction θ_m (relative to the *x* axis) and phase ψ_m.

If we assume that the phases are random, and that the wavenumber and frequency are related by a linear dispersion relation

$$(\sigma_m)^2 = g k_m \tanh k_m d \tag{2}$$

then we can define the directional wave spectrum $S(\sigma,\theta)$ from the sum of the squared amplitudes of all component sinusoids (proportional to the total wave energy) within a small range of frequencies and directions:

Spectral models such as SWAN then work on the basis of considering the transformation of wave

$$\frac{1}{d\sigma}\sum_{\sigma}^{\sigma+d\sigma}\frac{1}{d\theta}\sum_{\theta}^{\theta+d\theta}\tfrac{1}{2}A_m^2 = S(\sigma,\theta) \tag{3}$$

energy represented by the spectrum under the action of various physical processes. This is done through a spectral action balance equation:

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \tag{4}$$

Here $N = N(\sigma,\theta) = S(\sigma,\theta)/\sigma$ is the action density. The first term on the left hand side is the local rate of change of wave action density at a fixed point. The second and third

4 Agitation and Refraction with Telemac on a MIldSlope http://www.opentelemac.org/index.php/presentation?id=19

terms represent spatial advection, with c_x and c_y are components of the net wave propagation velocity (combining intrinsic wave group velocity with any ambient current), the fourth and fifth terms represent the shift in wave frequency and direction, respectively, due to refraction by varying depth and currents. The “source term” on the right hand side includes all other relevant physical processes, including energy input from the wind, dissipation, and nonlinear interactions.

2.2 The ARTEMIS phase-resolving wave model

The ARTEMIS wave model is a finite element phase-resolving wave module for the TELEMAC–MASCARET software. It is used to describe the combined effects of diffraction, refraction, reflection and wave breaking for water waves propagating over bathymetry and due to interactions with lateral boundaries—like breakwaters and coastlines.

The ARTEMIS code solves the extended elliptic mild-slope equation using finite element mesh techniques. The mild slope equation (Berkhoff 1972) is applicable for computations of refraction and diffraction of linear waves. The following elliptic form of the mild slope equation includes additional dissipative effects (Booij 1981).

$$\nabla(CC_g \nabla \phi) + CC_g (k^2 + ik\mu)\phi = 0 \tag{5}$$

where ϕ is the reduced two-dimensional velocity potential, $\mu = \frac{W}{(CC_g)^{1/2}}$ is the dissipation coefficient with W a dissipation function, k^2 is the wavenumber, C is the wave celerity and C_g is the group velocity of the waves. Usual approximations associated with linear theory apply, with irregular waves considered as the linear superposition of regular waves (Booij 1981).

To relate the spectral and potential descriptions of wave motion, we note that the reduced potential corresponding to the sum of sinusoids in Equation (1) is

$$\phi(x,y) = -i\sum_{m=1}^{M} gA_m \frac{gA_m}{\sigma_m} \exp i\left[k_m(x\cos\theta_m + y\sin\theta_m) + \psi_m\right] \tag{6}$$

ARTEMIS is an approximate model, deriving its name from being originally developed for wave propagation over mild slopes of the sea floor. The method is suitable for modelling wave resonance and seiching in harbours and wave fields due to combined refraction/diffraction/reflection in small bays. However refraction by currents is not included.

Since release 6.1, the TELEMAC ARTEMIS wave module can take into account the effects of a rapidly varying topography in the mild-slope equation. The main results are, for every node of the mesh, the height, the phase and the direction of the waves.

2.3 SWAN model implementation

The same spatial and spectral model grids used in the previous SWAN simulations (Gorman, Mullan et al. 2006) was again applied (Figure 2-1). That is, a grid of 100×129 cells at 100 m resolution oriented at 30° from a north-south alignment. The grid origin (cell (1,1)) was at NZMG (2657608.30E, 5986589.26N). The wave spectra had 25 discrete wave frequencies logarithmically placed between 0.0418 Hz and 0.802 Hz (or wave periods from 24 seconds down to 1.2 seconds), and 32 direction bins at 11.25° increments around the compass. All other model settings were SWAN defaults as described in the manual (Holthuijsen, Booij et al. 2000)).

As our region of interest is not exposed to swell entering through the harbour entrance, no input swell boundary conditions were applied at the open southern boundary of the model

Wind records were again taken from the Meteorological Station at Wellington Airport (latitude 41.322°S, longitude 174.804°E, elevation 43 m). Hourly measurements of average wind speed and direction (averaged over 10 minutes) for the full calendar years 1962-2004 were used.

In the previous study (Gorman, Mullan et al. 2006), a "scenario-based" approach to wave climate simulation was used. That involved running SWAN for a large number of scenarios, covering many combinations of wind speed, wind direction and tidal water level. This was used to develop a lookup table of model outputs at the selected output sites for each set of input conditions. Using that, for any given set of input conditions from a historic (or hypothetical) record, the resulting wave outputs could be estimated by interpolation from the site. This method allows long historic records to be simulated without the need for a prohibitively-long direct SWAN simulation.

The original simulations (Gorman, Mullan et al. 2006) provided a 43-year synthetic time series of wave conditions (significant height, mean and peak period, mean and peak direction) at selected sites around Wellington Harbour, of which "site 6" (at NZMG coordinates 2660014.52E, 5989356.95N, in water depth 10.6 m below Chart Datum) was the closest to our area of interest.

From this "site 6" record, storm peaks were identified using a "peaks over threshold" method. First, a "storm threshold" wave height H_{thresh} was selected, taken as the 95th percentile value of all significant wave height records in the "site 6" time series. This came to H_{thresh} = 0.29 m. Then storm peaks were selected as local maxima above this threshold, with successive peaks separated by at least 1 day.

From these storm events, the 200 largest peak wave heights were selected. The SWAN model was then rerun for each of these selected storm events. This was done as a direct simulation in stationary mode, i.e. applying the wind speed and direction, and the tidal elevation applying at the time, and letting the model converge to an equilibrium distribution of wave energy across the harbour.

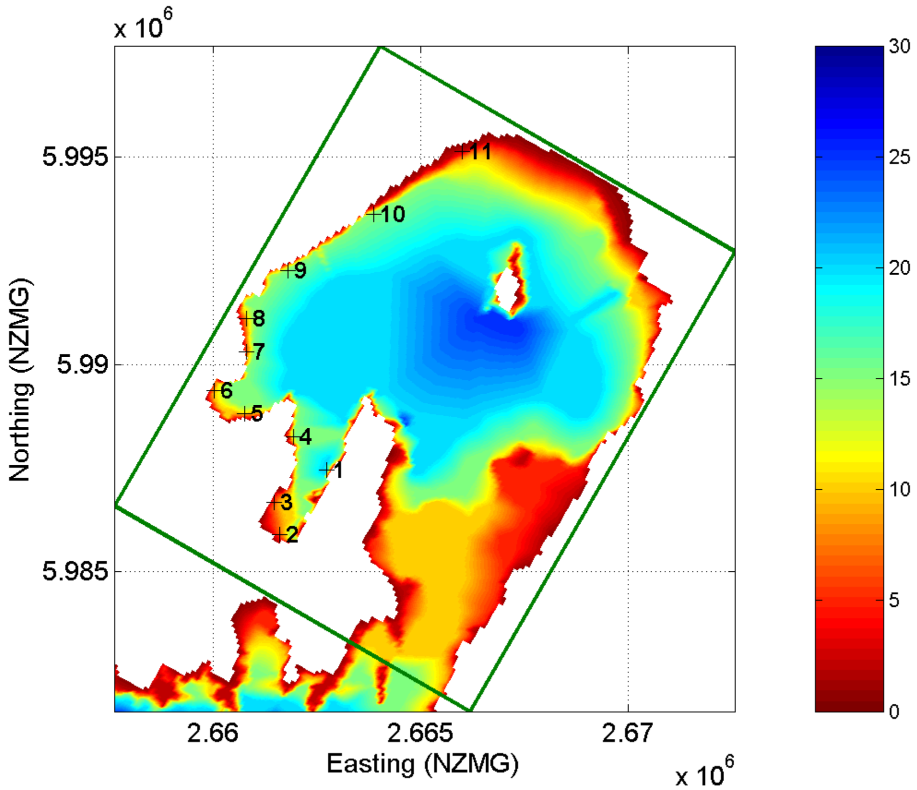


Figure 2-1: Location map of Wellington Harbour with water depth in metres below Chart Datum shown by the colour scale. The model domain used for wave simulations is marked by

the green rectangle, and the locations of numbered output sites from the 2006 study are marked.ARTEMIS model implementation

ARTEMIS was implemented on the domain illustrated in Figure 2-2. One of the challenges with ARTEMIS is that a fine or high-resolution mesh is required to cover at least 7 points within a wave length for the peak period and no less than 3 points across a wavelength for the shortest period. For the Wellington wave modelling, the wave periods of interest (at storm peaks) can be of order 4 seconds. This corresponds to wave lengths range of approximately 25m, so the grid resolution had to be refined down to a node spacing of approximately 5 m.

Table 2-1 represents the physical and numerical parameters used when running the ARTEMIS wave model.

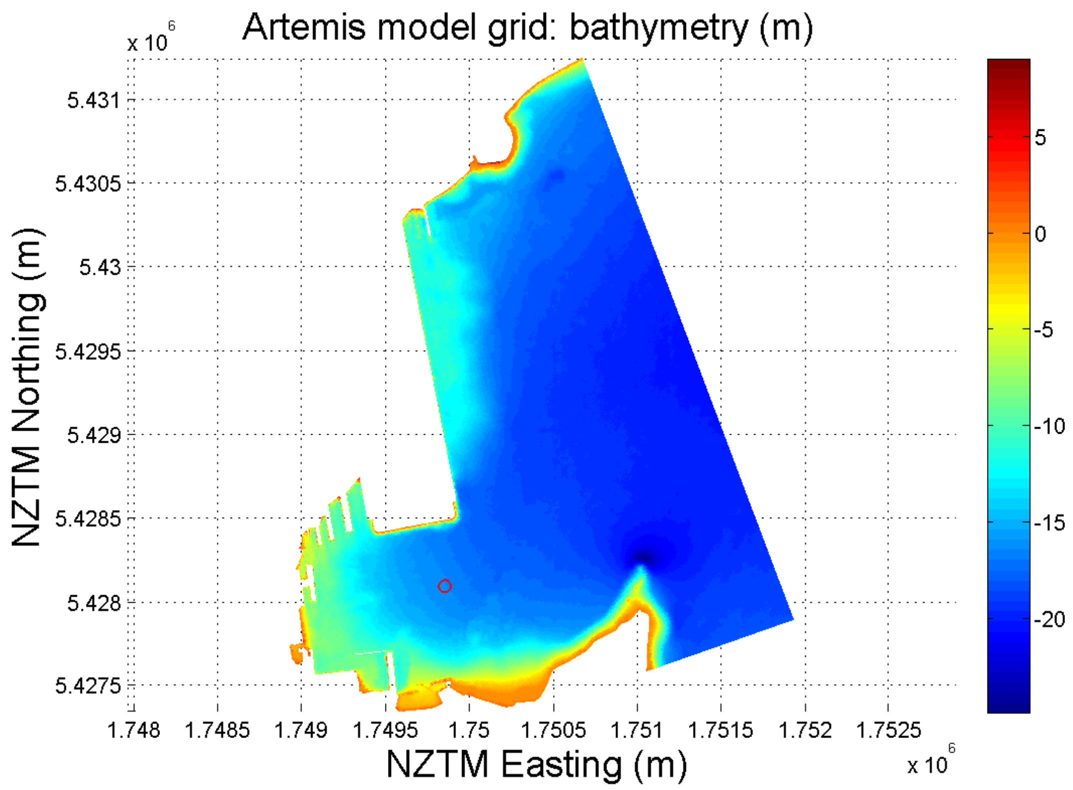


Figure 2-2: Model domain used for ARTEMIS simulations. Water depth in metres below Chart Datum is shown by the colour scale. The red circle marks the location from which SWAN outputs were used to provide ARTEMIS boundary conditions.Table 2-1: Physical and numerical parameters used in the set-up of ARTEMIS.

Monochromatic Waves	: Yes
Period Scanning	: No
Bathymetric Breaking	: Yes /Dally formulations for regular waves
GDALLY	: 0.35
KDALLY	: 0.100
Bottom friction	: Yes /constant
Rapidly varying topography	: 3 /both gradient and curvature effects
Dissipation coefficient	: 2 / Putman and Johnson's formula

Wave reflection at the shoreline is an important aspect of harbour wave agitation models. The reflection coefficient represents a ratio of the amplitude of the wave that approaches the coast to the amplitude that is reflected away from the coast. The reflection coefficient used in the model is based on results from Zanuttigh and van der Meer (Zanuttigh and van der Meer 2006). The ARTEMIS boundary file was modified to incorporate the following equations. Sensitivity testing showed that only the groyne structure and the front southern exposed end of the proposed airport were sensitive to the reflection coefficient. Nevertheless, the ARTEMIS model coastal boundary was divided into various sections and K_r was calculated for each section inside the model. This allowed the model to be run with period scanning and K_r to change accordingly.

$$K_r = tanh\left(a.{\xi_o}^b\right) \tag{7}$$

where the parameter ξ (expanded Iribarren number) represent bimodal spectra for shallow water with flat spectra (Zanuttigh and van der Meer 2006), defined as:

$$\xi = \frac{\tan\alpha}{\sqrt{(2\pi H_{m0})/\left(gT_{m-1,0}^2\right)}} \tag{8}$$

with the calibration values of the coefficients *a* and *b* which depend entirely on the structure surface. *H* is wave height, *g* is gravity and *T* wave period for a singled-peaked spectrum.

The offshore boundary conditions are parameterised with three key variables which are used to “drive” the model: direction of approaching waves, phase -shift, and incident wave height in this case for monochromatic waves. These were taken from the outputs of the SWAN simulations at a point marked in Figure 2-2, and applied at the open (eastern) boundary of the ARTEMIS grid. This SWAN output location was selected rather than a point on the boundary, so that the intervening wind-driven wave growth computed by SWAN, but not by ARTEMIS, could be accounted for.

Monochromatic simulations were run, with wave height, period and direction at the boundary derived from the significant wave height, the peak wave period and the mean wave direction provided by SWAN outputs.

Some of these incident wave events had incident wave directions from the SWAN outputs outside the range for which an accurate ARTEMIS simulation could be applied (less than 120° from the *x* axis). These events were not simulated, leaving a total of 175 simulations.

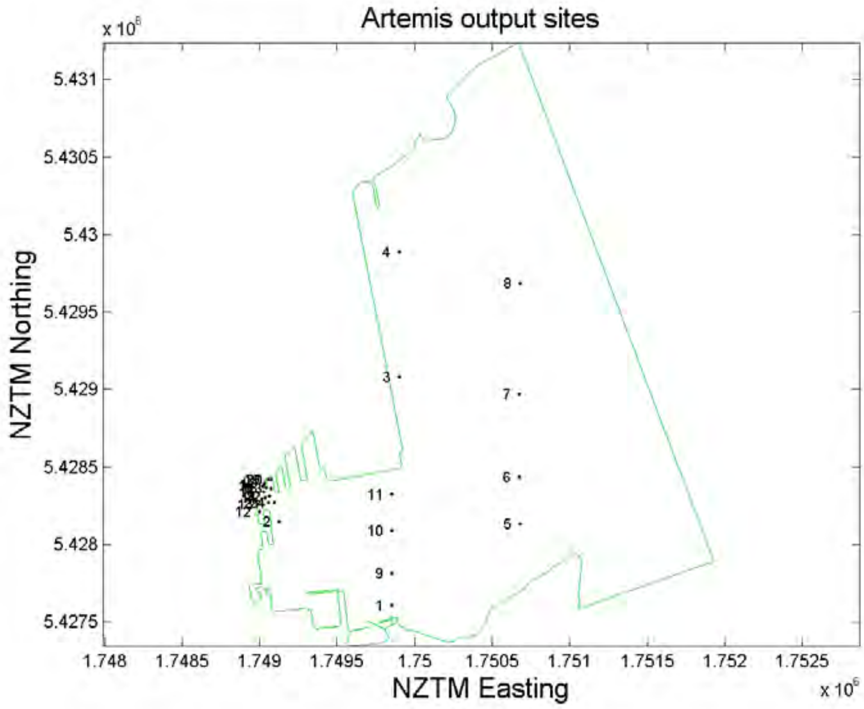
Wave statistics were extracted from the ARTEMIS simulations at a set of 24 output locations, listed in Table 2-2 and plotted in Figure 2-3.

As an example, Figure 2-4 shows the time series of storm peak values of significant wave height at site 2, near the Queen’s Wharf area. These are plotted alongside the storm peak values from the 2006 study at the original site 6, and the values obtained when the 200 largest peaks were re-run in SWAN. We firstly note that revised SWAN simulation method has produced a notable increase (of order 50%) in storm peak wave heights at SWAN site 6 compared to the 2006 study. However the Artemis simulation produces a much greater subsequent *reduction* (by a factor around ¼) in bringing those wave heights into the vicinity of the Wellington water front.

This reduction can be better illustrated by Figure 2-5, which shows the mean value, averaged across all ARTEMIS simulations, of significant wave height over the ARTEMIS domain. Over the outer part of the domain there is a moderate level of spatial variability associated with local bathymetry. But much larger spatial variability is seen where the wave field is obstructed by coastal features, particularly the large Centre Port reclamation, which provides considerable sheltering from waves incident from the NE quadrant.

Table 2-2: Location of output sites from ARTEMIS modelling.

	NZTM coordinates	
Output site number	Easting	Northing
1	1749854.5	5427607.5
2	1749124.1	5428146.0
3	1749899.4	5429082.5
4	1749900.5	5429890.0
5	1750677.8	5428132.0
6	1750677.4	5428436.5
7	1750674.4	5428970.0
8	1750677.8	5429685.5
9	1749852.5	5427814.5
10	1749853.0	5428088.5
11	1749854.0	5428321.0
12	1748997.3	5428211.5
13	1749017.5	5428261.5
14	1749035.3	5428303.5
15	1749024.5	5428339.0
16	1749020.5	5428378.0
17	1749030.6	5428393.5
18	1749041.4	5428364.0
19	1749056.6	5428419.5
20	1749074.9	5428420.0
21	1749058.1	5428271.5
22	1749061.6	5428312.0
23	1749071.5	5428361.0
24	1749093.6	5428270.5


Artemis output sites
NZTM Northing
NZTM Easting
x 10^6
5.431
5.4305
5.43
5.4295
5.429
5.4285
5.428
5.4275
1.748
1.7485
1.749
1.7495
1.75
1.7505
1.751
1.7515
1.752
1.7525
1
2
3
4
5
6
7
8
9
10
11
12

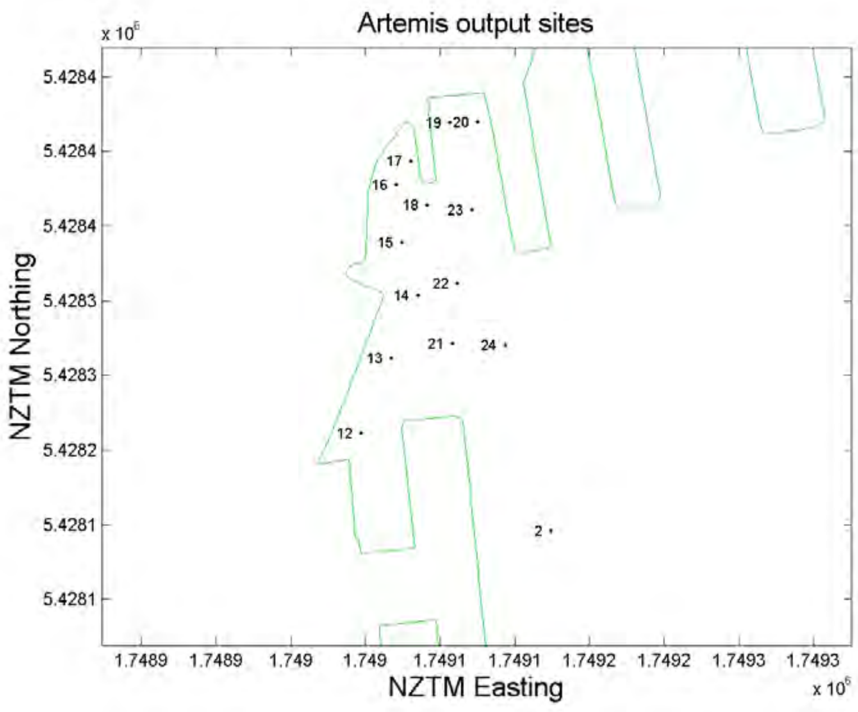

Artemis output sites
NZTM Northing
NZTM Easting
x 10^6
5.4284
5.4284
5.4284
5.4283
5.4283
5.4282
5.4281
5.4281
1.7489
1.7489
1.749
1.749
1.7491
1.7491
1.7492
1.7492
1.7493
1.7493
2
12
13
14
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Figure 2-3: Output sites from the ARTEMIS simulations. Top panel: full model domain, bottom panel: Queens Wharf area.

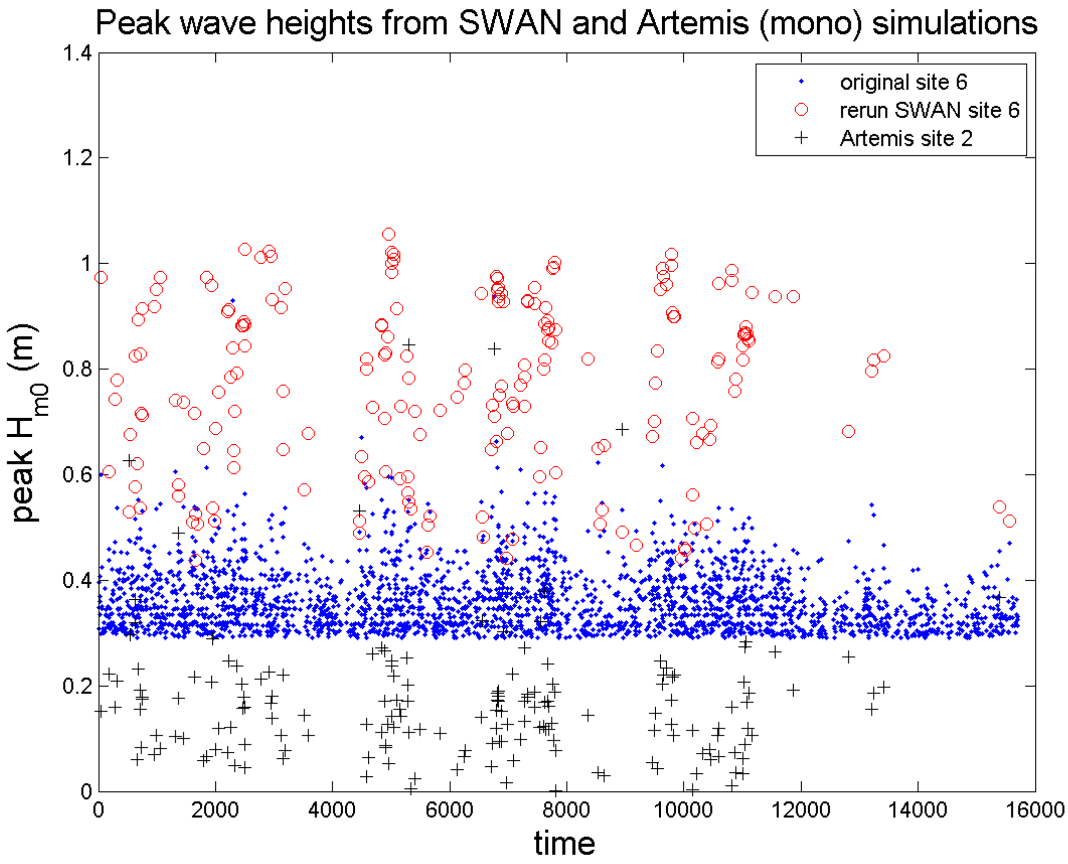

Figure 2-4: Time series of storm peak significant wave heights from wave model simulations. Blue dots show all peak wave heights from derived from the original (2006) simulated time series at "site 6". Red circles show the results of rerunning SWAN for the largest 200 of those events. Black crosses show the outputs at (ARTEMIS output) site 2 of the corresponding ARTEMIS simulation.

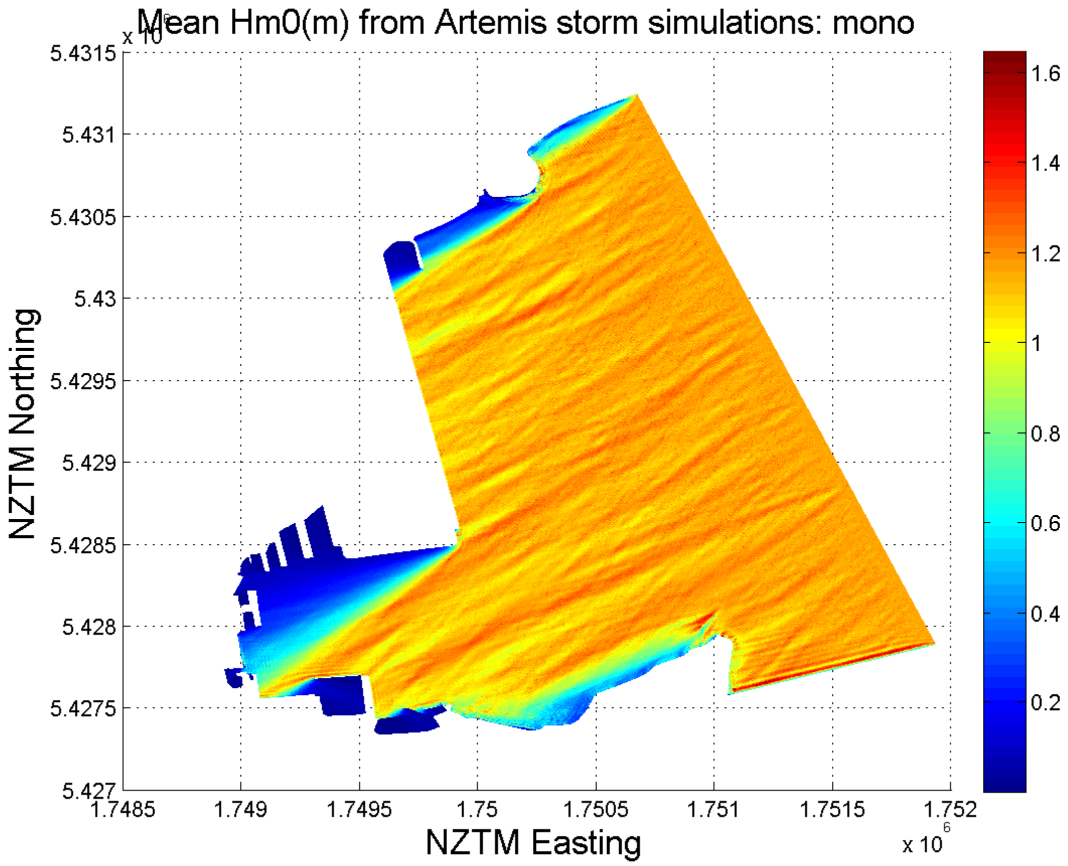

Figure 2-5: Mean value of significant wave height over all ARTEMIS monochromatic simulations.

2.5 Extreme wave analysis

The wave modelling procedure described above results in outputs at each selected location consisting of the largest storm peak wave heights (H_{peak}) for the 43 year study period. In order to produce return values, the following procedure was carried out:

Firstly, a Generalised Pareto Distribution

$$CDF(H_{peak}) = 1 - \left(1 + \frac{k(H_{peak} - H_{thresh})}{\sigma}\right)^{-1/k} \tag{9}$$

was fitted to the cumulative distribution of peak wave heights. In this fit, the threshold H_{thresh} was fixed as 95% of the minimum of the set of H_{peak} values, while the shape parameter k and the scale parameter σ were treated as adjustable fitting parameters.

The fitted distribution was then inverted to find return values of H_{peak} corresponding to Annual Exceedance Probability (AEP) values of 0.632, 0.394, 0.181, 0.095, 0.049, 0.020, 0.010 (equating to return intervals of 1, 2, 5, 10, 20, 50 and 100 years, respectively).

In the first instance, this method was applied to the same storm peak values obtained at site 6 in the original study (Gorman, Mullan et al. 2006). The resulting return values are listed in Table 2-3, alongside the return values calculated in that study by a slightly different method, i.e. fitting a 3-parameter Weibull distribution to a much larger set of storm peaks. We see that the results are almost identical, the largest discrepancy being 3mm in the 0.01 AEP wave height.

Next we computed return wave heights from the revisited SWAN simulation at the original site 6, also listed in Table 2-3. These figures again show that the method of using direct stationary SWAN simulations produces larger values of storm wave heights, by around 50%, than were obtained using the “scenario-based” method. Hence basing wave climate statistics on the revised SWAN modelling approach provides a more conservative approach to wave climate estimation for design purposes than direct application of the 2006 study.

The 2006 study also carried out simulations accounting for the effects of climate change, including simulations applicable for 50 years into the future (nominally for 2050) assuming a 10% increase in wind speeds accompanied by a 16 cm rise in mean sea level, and for a 100 year projection (nominally for 2100) assuming a 20% increase in wind speeds and a 40 cm sea level rise. We have taken the outputs from those 2006 simulations and computed the corresponding return values of storm peak significant wave height. These results are also listed in Table 2-3.

Return values of storm peak significant wave height calculated from the Artemis simulations are listed in Table 2-4. We can group the ARTEMIS output sites into two sets: more exposed outer sites (1, and 3-11), and more sheltered sites (2, and 12-24) in the Queen’s Wharf area. For the former group, 0.01 AEP peak wave heights range from 1.6 – 2.1 m, while the latter group have 0.01 AEP values less than 1 m, with some considerably less depending on their degree of protection by local wharf structures: for example sites 15, 16 and 17 along the Kumutoto Wharf have 0.01 AEP values of 0.29 m, 0.18 m and 0.05 m, respectively.

It might be noted that the spatial variability of these results will be somewhat sensitive to details of the seabed and shoreline topography, and of the wave absorption & reflection characteristics of the shoreline and wharves, that may not be represented with complete fidelity in the ARTEMIS model. Hence a conservative application of these results might be taken.

Estimates of the corresponding return statistics under climate change conditions were then made. For the purposes of revising the wave statistics, we considered the same scenarios investigated in the 2006 study. To do so, we assumed that the same relative change in return wave heights computed at the original site 6 from the 2006 simulations (listed in Table 2-3) will also apply to the other sites investigated in the present study. Thus, for example, all 0.01 AEP wave heights for the 2050 climate are scaled up from values for the present day climate by a factor 0.86/0.75 observed between 0.01 AEP wave heights for 2050 and present day wave climates computed from site 6 records in the 2006 study. Results of these estimates are presented in Table 2-5 for the 50 year climate change projection (with a 10% increase in wind speed), and in Table 2-6 for the 100 year projection (with a 20% increase in wind speed). It should be noted that the associated sea level rises (0.15 m and 0.40 m) used in the wave studies are not consistent with more recent guidance of 1.0 m by 2115, but a correction for this will be applied in reanalysis of sea level statistics described later in Section 2.6.

Table 2-3: Return values of storm peak significant wave height at output site 6 from the 2006 study. Results (for 1962-2014 wave climate) are given as reported in the 2006 study, from the new SWAN simulations in the present study, and as recomputed from the 2006 study outputs, for which figures for “2050 climate” (assuming a 10% increase in wind speed, and a 16 cm sea level rise), and “2100 climate” (assuming a 20% increase in wind speed, and a 40 cm sea level rise) are also given. The wave height threshold used in the POT analysis is given in column 2.

		Annual Exceedance Probability						
		0.632	0.393	0.181	0.095	0.049	0.020	0.010
		Average Return Interval (years)						
		1	2	5	10	20	50	100
	Height threshold (m)	Peak significant wave height (m)						
1962-2014 climate: computed in 2006 study		0.54			0.66	0.70	0.74	0.78
1962-2014 climate: present study	0.45	0.93	0.99	1.03	1.04	1.05	1.05	1.05
recomputed from 2006 study outputs:								
1962-2014 climate	0.29	0.55	0.59	0.63	0.66	0.69	0.73	0.75
2050 climate	0.33	0.63	0.67	0.72	0.75	0.79	0.83	0.86
2100 climate	0.37	0.70	0.75	0.81	0.85	0.89	0.94	0.98

Table 2-4: Return values of storm peak significant wave height at ARTEMIS output sites (monochromatic simulations) under present day (i.e. 1962-2014) climate conditions. The wave height threshold used in the POT analysis is given in column 2.

		Annual Exceedance Probability						
		0.632	0.393	0.181	0.095	0.049	0.020	0.010
		Average Return Interval (years)						
		1	2	5	10	20	50	100
Output site number	Height threshold (m)	Peak significant wave height (m)						
1	0.62	1.35	1.54	1.68	1.74	1.77	1.8	1.81
2	0.10	0.21	0.29	0.40	0.49	0.58	0.71	0.81
3	0.65	1.36	1.53	1.65	1.71	1.74	1.76	1.77
4	0.64	1.37	1.49	1.57	1.59	1.6	1.61	1.61
5	0.65	1.36	1.54	1.66	1.72	1.75	1.77	1.78
6	0.67	1.39	1.55	1.66	1.70	1.73	1.74	1.75
7	0.63	1.31	1.46	1.58	1.62	1.65	1.67	1.68
8	0.66	1.36	1.51	1.62	1.66	1.68	1.70	1.70
9	0.70	1.53	1.76	1.92	1.99	2.03	2.06	2.08
10	0.62	1.30	1.46	1.57	1.62	1.65	1.67	1.67
11	0.70	1.49	1.71	1.88	1.96	2.01	2.06	2.08
12	0.01	0.04	0.05	0.07	0.08	0.09	0.10	0.10
13	0.05	0.09	0.13	0.21	0.29	0.40	0.59	0.79
14	0.06	0.11	0.15	0.22	0.28	0.35	0.48	0.59
15	0.03	0.06	0.09	0.12	0.16	0.19	0.25	0.29
16	0.02	0.04	0.06	0.08	0.10	0.12	0.15	0.18
17	0.01	0.01	0.02	0.03	0.03	0.04	0.04	0.05
18	0.02	0.05	0.06	0.09	0.11	0.13	0.15	0.17
19	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.04
20	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03
21	0.06	0.12	0.17	0.24	0.31	0.40	0.53	0.66
22	0.05	0.10	0.14	0.21	0.27	0.34	0.46	0.58
23	0.02	0.04	0.05	0.07	0.09	0.11	0.14	0.16
24	0.05	0.11	0.16	0.24	0.32	0.41	0.57	0.71

Table 2-5: Return values of storm peak significant wave height at ARTEMIS output sites (monochromatic simulations) under a 50 year climate change projection. These results assume a 10% increase in wind. The wave height threshold used in the POT analysis is given in column 2.

		Annual Exceedance Probability						
		0.632	0.393	0.181	0.095	0.049	0.020	0.010
		Average Return Interval (years)						
		1	2	5	10	20	50	100
Output site number	Height threshold (m)	Peak significant wave height (m)						
1	0.71	1.55	1.75	1.92	1.98	2.03	2.05	2.08
2	0.11	0.24	0.33	0.46	0.56	0.66	0.81	0.93
3	0.74	1.56	1.74	1.89	1.94	1.99	2.00	2.03
4	0.73	1.57	1.69	1.79	1.81	1.83	1.83	1.85
5	0.74	1.56	1.75	1.90	1.95	2.00	2.01	2.04
6	0.76	1.59	1.76	1.90	1.93	1.98	1.98	2.01
7	0.72	1.50	1.66	1.81	1.84	1.89	1.90	1.93
8	0.75	1.56	1.71	1.85	1.89	1.92	1.93	1.95
9	0.80	1.75	2.00	2.19	2.26	2.32	2.34	2.39
10	0.71	1.49	1.66	1.79	1.84	1.89	1.90	1.91
11	0.80	1.71	1.94	2.15	2.23	2.30	2.34	2.39
12	0.01	0.05	0.06	0.08	0.09	0.10	0.11	0.11
13	0.06	0.10	0.15	0.24	0.33	0.46	0.67	0.91
14	0.07	0.13	0.17	0.25	0.32	0.40	0.55	0.68
15	0.03	0.07	0.10	0.14	0.18	0.22	0.28	0.33
16	0.02	0.05	0.07	0.09	0.11	0.14	0.17	0.21
17	0.01	0.01	0.02	0.03	0.03	0.05	0.05	0.06
18	0.02	0.06	0.07	0.10	0.13	0.15	0.17	0.19
19	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.05
20	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03
21	0.07	0.14	0.19	0.27	0.35	0.46	0.60	0.76
22	0.06	0.11	0.16	0.24	0.31	0.39	0.52	0.67
23	0.02	0.05	0.06	0.08	0.10	0.13	0.16	0.18
24	0.06	0.13	0.18	0.27	0.36	0.47	0.65	0.81

Table 2-6: Return values of storm peak significant wave height at ARTEMIS output sites (monochromatic simulations) under a 100 year climate change projection. These results assume a 20% increase in wind. The wave height threshold used in the POT analysis is given in column 2.

		Annual Exceedance Probability						
		1	0.5	0.2	0.1	0.05	0.02	0.01
Output site number	Height threshold (m)	Peak significant wave height (m)						
1	0.79	1.72	1.96	2.16	2.24	2.28	2.32	2.37
2	0.13	0.27	0.37	0.51	0.63	0.75	0.91	1.06
3	0.83	1.73	1.94	2.12	2.20	2.24	2.27	2.31
4	0.82	1.74	1.89	2.02	2.05	2.06	2.07	2.10
5	0.83	1.73	1.96	2.13	2.22	2.26	2.28	2.33
6	0.85	1.77	1.97	2.13	2.19	2.23	2.24	2.29
7	0.80	1.67	1.86	2.03	2.09	2.13	2.15	2.20
8	0.84	1.73	1.92	2.08	2.14	2.17	2.19	2.22
9	0.89	1.95	2.24	2.47	2.56	2.62	2.65	2.72
10	0.79	1.65	1.86	2.02	2.09	2.13	2.15	2.18
11	0.89	1.90	2.17	2.42	2.52	2.59	2.65	2.72
12	0.01	0.05	0.06	0.09	0.10	0.12	0.13	0.13
13	0.06	0.11	0.17	0.27	0.37	0.52	0.76	1.03
14	0.08	0.14	0.19	0.28	0.36	0.45	0.62	0.77
15	0.04	0.08	0.11	0.15	0.21	0.25	0.32	0.38
16	0.03	0.05	0.08	0.10	0.13	0.15	0.19	0.24
17	0.01	0.01	0.03	0.04	0.04	0.05	0.05	0.07
18	0.03	0.06	0.08	0.12	0.14	0.17	0.19	0.22
19	0.01	0.01	0.03	0.03	0.04	0.04	0.04	0.05
20	0.00	0.01	0.01	0.03	0.03	0.03	0.04	0.04
21	0.08	0.15	0.22	0.31	0.40	0.52	0.68	0.86
22	0.06	0.13	0.18	0.27	0.35	0.44	0.59	0.76
23	0.03	0.05	0.06	0.09	0.12	0.14	0.18	0.21
24	0.06	0.14	0.20	0.31	0.41	0.53	0.73	0.93

2.6 Revised extreme sea level analysis

Since the 2006 study some more advanced methods have been developed to provide reliable estimates of extreme sea level statistics (Goring, Stephens et al. 2011). Hence we have revisited the available records from the Queens Wharf tide gauge, applying the Monte Carlo joint-probability (MCJP) method to fit hourly data from 2002-2013 inclusive. The storm-surge distribution used in the MCJP technique was based on a Generalised Pareto Distribution fit to Peaks Over Threshold data.

By way of comparison, the generalised extreme value distribution was also fitted to annual maxima from 1945-2013 inclusive, after detrending to remove a linear Sea Level Rise rate of 0.22 m (Hannah and Bell 2012).

The two distributions, along with their 95% Confidence Limits, are plotted in Figure 2-6. We note the relatively tight confidence bounds obtained from the MCJP method, and its consistency with other estimators.

So far, all sea level statistics have been referred to the Mean Sea Level (MSL). In previous work (Gorman, Mullan et al. 2006) MSL was referred to as Mean Level of the Sea (MLOS) applying during the study period. There is an interannual variation in MSL, averaging 1.080 m above Chart Datum over the period 1990-2005 (Gorman, Mullan et al. 2006). Wellington Chart Datum is defined as 3.002 m below B.M. K80/1, a stainless steel pin set in concrete under iron cover, in Featherston Street at the intersection with Lambton Quay. The Wellington Vertical Datum of 1953 (WVD-53) can also be used: this is 0.915 m above Chart Datum.

The mean sea level datums for relevant periods were calculated from annual mean sea levels, and are listed in Table 2-7.

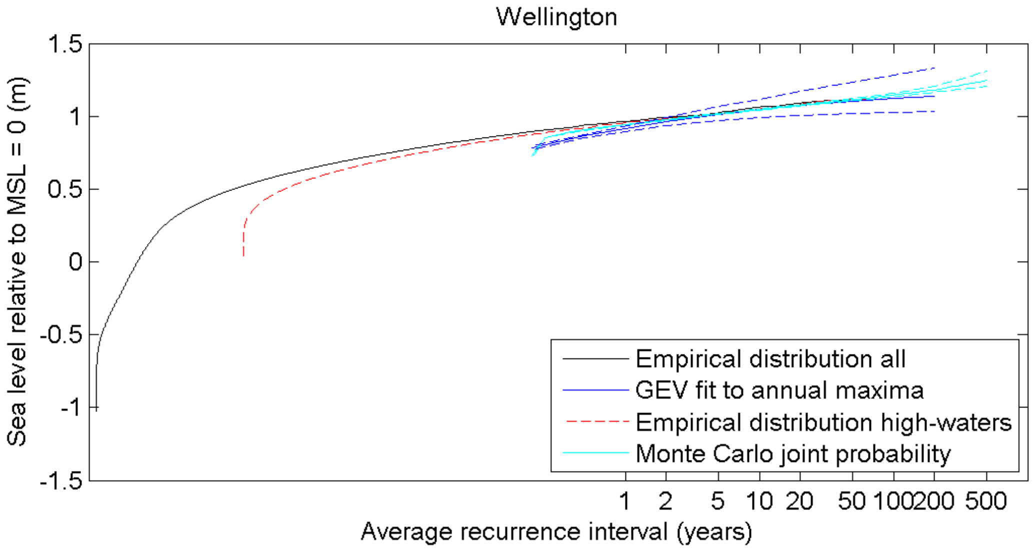

Figure 2-6: Recurrence values for extreme sea levels at Queen's Wharf. Values are shown relative to mean sea level. Estimates are show with 95% confidence levels for the Monte Carlo joint probability method applied to hourly data from 2002-2013 and for the GEV method applied to annual maxima from 1945-2013.

Table 2-7: Mean sea level relative to WVD-53.

MSL	Epoch	Description
0.166	1985-2005	IPCC AR% baseline epoch for SLR projections
0.194	1995-2013	recent 19-year tidal epoch
0.208	2004-2013	Recent decade

2.7 Joint exceedance statistics

In the 2006 study, estimates were made of joint annual exceedance statistics for water levels and peak wave heights. These were presented as tables giving combinations of water level relative to MSL (or MLOS in the 2006 report) and significant wave height at each location (e.g. at site 6) that can expect to be exceeded that have specified Annual Exceedance Probabilities.

We have used the revised wave modelling to update those tables to account for the replacement of wave conditions previously modelled at the original site 6 with the new simulations of the same events at locations along the waterfront. As the sea level statistics can be taken to apply throughout the study region, we have taken the original tables (Tables A3.6, A3.17, A3.28) from the 2006 report (Gorman, Mullan et al. 2006), and rescaled the "site 6" wave height figures to corresponding values for each ARTEMIS output site (14-18). The scaling factor used for joint exceedance height levels was the ratio between the *marginal* return heights from the new simulation at the relevant site (as in Table 2-4), and the original site 6 (Table 2-5), for the relevant AEP.

Next, the revision of sea level extreme value statistics described in Section 2.6 was also taken into account. We chose to replace the extreme sea level distribution results from the 2006 study with the distribution obtained from Monte Carlo joint-probability method. The (marginal) Annual Exceedance Probability for sea level to exceed a certain value is identical to the joint AEP for the same level to be exceeded in combination with any wave height over zero. This immediately gives the revised value of the zero wave height end of each contour. The same sea level offset was then be applied to the rest of the contour. This gives a corrected sea level relative to the relevant Mean Sea Level, to which an offset can be applied to give levels relative to WVD-53.

The joint exceedance statistics obtained in this way for the present-day climate are shown in
Table 2-8. In this case the 2004–2013 MSL offset of 0.208 m was added to the MCJP analysis to derive extreme sea levels relative to WVD-53. Results for 2050 and 2100 climates are given in
Table 2-9 and Table 2-10, respectively. Noting that more recent guidance indicates that a 1.0 m sea level rise should be taken into account over the next 100 years, for the 2050 and 2100 climate change scenarios additional offsets of 0.50 m and 1.0 m, respectively, have been applied to convert to expected levels relative to WVD-53. We note that the respective 15 cm and 40 cm assumed sea level rises built into the original wave simulations have not been changed, but note that the direct effect of sea level changes on wave conditions is relatively minor compared to the increased wind speed.

Table 2-8: Combinations of sea level and wave height at selected ARTEMIS output sites with specified joint annual exceedance probabilities, under present climate conditions. Sea levels in the third column are referred to the present day mean sea level, which is taken to be 0.208 m above WVD-53. In column 4, this offset is added in to give levels relative to WVD-53.

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.632	1	0.00	0.21	0.082	0.047	0.030	0.011	0.035
0.632	1	0.13	0.34	0.082	0.047	0.030	0.011	0.035
0.632	1	0.33	0.54	0.080	0.046	0.030	0.011	0.034
0.632	1	0.53	0.74	0.074	0.042	0.027	0.010	0.032
0.632	1	0.63	0.84	0.068	0.039	0.025	0.009	0.029
0.632	1	0.73	0.94	0.058	0.033	0.022	0.008	0.025
0.632	1	0.73	0.94	0.058	0.033	0.022	0.008	0.025
0.632	1	0.83	1.04	0.041	0.023	0.015	0.005	0.018
0.632	1	0.90	1.11	0.019	0.011	0.007	0.003	0.008

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.632	1	0.92	1.13	0.010	0.006	0.004	0.001	0.004
0.632	1	0.93	1.14	0.006	0.003	0.002	0.001	0.003
0.632	1	0.94	1.15	0.000	0.000	0.000	0.000	0.000
0.095	10	0.00	0.21	0.203	0.114	0.071	0.023	0.077
0.095	10	0.13	0.34	0.203	0.114	0.071	0.023	0.077
0.095	10	0.33	0.54	0.198	0.111	0.070	0.022	0.075
0.095	10	0.53	0.74	0.190	0.106	0.067	0.021	0.072
0.095	10	0.63	0.84	0.181	0.102	0.064	0.020	0.069
0.095	10	0.73	0.94	0.169	0.095	0.060	0.019	0.064
0.095	10	0.83	1.04	0.148	0.083	0.052	0.016	0.056
0.632	10	0.89	1.10	0.127	0.071	0.045	0.014	0.048
0.095	10	0.93	1.14	0.110	0.062	0.039	0.012	0.042
0.095	10	1.02	1.23	0.042	0.024	0.015	0.005	0.016
0.095	10	1.03	1.24	0.021	0.012	0.007	0.002	0.008
0.632	10	1.04	1.25	0.000	0.000	0.000	0.000	0.000
0.02	50	0.00	0.21	0.333	0.172	0.107	0.031	0.107
0.02	50	0.12	0.33	0.333	0.172	0.107	0.031	0.107
0.02	50	0.32	0.53	0.333	0.172	0.107	0.031	0.107
0.02	50	0.40	0.61	0.327	0.169	0.105	0.030	0.105
0.02	50	0.52	0.73	0.320	0.165	0.103	0.029	0.103
0.02	50	0.62	0.83	0.307	0.159	0.099	0.028	0.098
0.02	50	0.72	0.93	0.287	0.148	0.092	0.026	0.092
0.02	50	0.82	1.03	0.268	0.138	0.086	0.025	0.086
0.02	50	0.92	1.13	0.222	0.115	0.071	0.020	0.071
0.02	50	0.98	1.19	0.196	0.101	0.063	0.018	0.063
0.02	50	1.08	1.29	0.065	0.034	0.021	0.006	0.021
0.02	50	1.09	1.30	0.033	0.017	0.011	0.003	0.010
0.02	50	1.11	1.32	0.000	0.000	0.000	0.000	0.000
0.01	100	0.00	0.21	0.406	0.201	0.125	0.034	0.120
0.01	100	0.14	0.34	0.406	0.201	0.125	0.034	0.120
0.01	100	0.34	0.54	0.406	0.201	0.125	0.034	0.120
0.01	100	0.51	0.71	0.390	0.193	0.120	0.033	0.115
0.01	100	0.54	0.74	0.390	0.193	0.120	0.033	0.115
0.01	100	0.64	0.84	0.382	0.189	0.117	0.032	0.113
0.01	100	0.74	0.94	0.359	0.178	0.110	0.030	0.106
0.01	100	0.84	1.04	0.343	0.170	0.105	0.029	0.101
0.01	100	0.94	1.14	0.289	0.143	0.089	0.024	0.085
0.01	100	1.04	1.24	0.234	0.116	0.072	0.020	0.069
0.01	100	1.14	1.34	0.078	0.039	0.024	0.007	0.023

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.01	100	1.14	1.34	0.039	0.019	0.012	0.003	0.012
0.01	100	1.15	1.35	0.000	0.000	0.000	0.000	0.000
0.005	200	0.00	0.21	0.501	0.237	0.147	0.038	0.136
0.005	200	0.14	0.35	0.501	0.237	0.147	0.038	0.136
0.005	200	0.34	0.55	0.482	0.228	0.141	0.037	0.131
0.005	200	0.54	0.75	0.473	0.224	0.138	0.036	0.129
0.005	200	0.63	0.84	0.464	0.219	0.136	0.035	0.126
0.005	200	0.64	0.85	0.464	0.219	0.136	0.035	0.126
0.005	200	0.74	0.95	0.445	0.211	0.130	0.034	0.121
0.005	200	0.84	1.05	0.418	0.197	0.122	0.032	0.113
0.005	200	0.94	1.15	0.399	0.189	0.117	0.030	0.108
0.005	200	1.06	1.27	0.278	0.132	0.081	0.021	0.076
0.005	200	1.16	1.37	0.046	0.022	0.014	0.004	0.013
0.005	200	1.16	1.37	0.093	0.044	0.027	0.007	0.025
0.005	200	1.18	1.39	0.000	0.000	0.000	0.000	0.000
0.002	500	0.00	0.21	0.639	0.283	0.175	0.043	0.155
0.002	500	0.17	0.38	0.639	0.283	0.175	0.043	0.155
0.002	500	0.37	0.58	0.639	0.283	0.175	0.043	0.155
0.002	500	0.57	0.78	0.616	0.273	0.168	0.041	0.149
0.002	500	0.67	0.88	0.593	0.263	0.162	0.040	0.143
0.002	500	0.71	0.92	0.581	0.257	0.159	0.039	0.140
0.002	500	0.77	0.98	0.581	0.257	0.159	0.039	0.140
0.002	500	0.87	1.08	0.581	0.257	0.159	0.039	0.140
0.002	500	0.97	1.18	0.523	0.232	0.143	0.035	0.126
0.002	500	1.14	1.35	0.349	0.154	0.095	0.023	0.084
0.002	500	1.24	1.45	0.000	0.000	0.000	0.000	0.000

Table 2-9: Combinations of sea level and wave height at selected ARTEMIS output sites with specified joint annual exceedance probabilities, under a 50 year climate change scenario. Sea levels in the third column are referred to the projected mean sea level, which is assumed to be 0.5m above present mean sea level. In column 4, these offsets are added in to give levels relative to WVD-53.

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.632	1	0.00	0.71	0.091	0.052	0.034	0.012	0.040
0.632	1	0.18	0.89	0.091	0.052	0.034	0.012	0.040
0.632	1	0.38	1.09	0.090	0.051	0.033	0.012	0.039
0.632	1	0.58	1.29	0.082	0.047	0.030	0.011	0.035
0.632	1	0.63	1.34	0.078	0.044	0.029	0.010	0.034
0.632	1	0.78	1.49	0.060	0.034	0.022	0.008	0.026
0.632	1	0.87	1.58	0.039	0.022	0.014	0.005	0.017

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.632	1	0.88	1.59	0.035	0.020	0.013	0.005	0.015
0.632	1	0.91	1.62	0.019	0.011	0.007	0.003	0.008
0.632	1	0.94	1.65	0.000	0.000	0.000	0.000	0.000
0.095	10	0.00	0.71	0.228	0.128	0.080	0.025	0.086
0.095	10	0.17	0.88	0.228	0.128	0.080	0.025	0.086
0.095	10	0.37	1.08	0.224	0.125	0.079	0.025	0.085
0.095	10	0.57	1.28	0.211	0.118	0.074	0.024	0.080
0.095	10	0.77	1.48	0.181	0.102	0.064	0.020	0.069
0.095	10	0.82	1.53	0.169	0.095	0.060	0.019	0.064
0.095	10	0.87	1.58	0.148	0.083	0.052	0.016	0.056
0.095	10	0.97	1.68	0.105	0.059	0.037	0.012	0.040
0.095	10	1.00	1.71	0.084	0.047	0.030	0.009	0.032
0.095	10	1.02	1.73	0.042	0.024	0.015	0.005	0.016
0.095	10	1.04	1.75	0.000	0.000	0.000	0.000	0.000
0.02	50	0.00	0.71	0.379	0.196	0.122	0.035	0.121
0.02	50	0.17	0.88	0.379	0.196	0.122	0.035	0.121
0.02	50	0.37	1.08	0.372	0.192	0.120	0.034	0.119
0.02	50	0.57	1.28	0.359	0.186	0.116	0.033	0.115
0.02	50	0.77	1.48	0.313	0.162	0.101	0.029	0.100
0.02	50	0.87	1.58	0.287	0.148	0.092	0.026	0.092
0.02	50	0.92	1.63	0.261	0.135	0.084	0.024	0.084
0.02	50	0.97	1.68	0.235	0.121	0.076	0.022	0.075
0.02	50	1.08	1.79	0.131	0.067	0.042	0.012	0.042
0.02	50	1.10	1.81	0.065	0.034	0.021	0.006	0.021
0.02	50	1.11	1.82	0.000	0.000	0.000	0.000	0.000
0.01	100	0.00	0.71	0.460	0.228	0.141	0.039	0.136
0.01	100	0.18	0.88	0.460	0.228	0.141	0.039	0.136
0.01	100	0.38	1.08	0.460	0.228	0.141	0.039	0.136
0.01	100	0.58	1.28	0.445	0.220	0.137	0.037	0.131
0.01	100	0.78	1.48	0.390	0.193	0.120	0.033	0.115
0.01	100	0.88	1.58	0.374	0.185	0.115	0.031	0.111
0.01	100	0.98	1.68	0.312	0.154	0.096	0.026	0.092
0.01	100	0.98	1.68	0.312	0.154	0.096	0.026	0.092
0.01	100	1.11	1.81	0.156	0.077	0.048	0.013	0.046
0.01	100	1.14	1.84	0.078	0.039	0.024	0.007	0.023
0.01	100	1.15	1.85	0.000	0.000	0.000	0.000	0.000
0.005	200	0.00	0.71	0.557	0.263	0.163	0.043	0.151
0.005	200	0.19	0.90	0.557	0.263	0.163	0.043	0.151
0.005	200	0.39	1.10	0.557	0.263	0.163	0.043	0.151

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.005	200	0.59	1.30	0.547	0.259	0.160	0.042	0.149
0.005	200	0.79	1.50	0.482	0.228	0.141	0.037	0.131
0.005	200	0.89	1.60	0.455	0.215	0.133	0.035	0.124
0.005	200	0.99	1.70	0.418	0.197	0.122	0.032	0.113
0.005	200	1.03	1.74	0.371	0.175	0.109	0.028	0.101
0.005	200	1.13	1.84	0.186	0.088	0.054	0.014	0.050
0.005	200	1.17	1.88	0.093	0.044	0.027	0.007	0.025
0.005	200	1.18	1.89	0.000	0.000	0.000	0.000	0.000
0.002	500	0.00	0.71	0.709	0.314	0.194	0.048	0.171
0.002	500	0.17	0.88	0.709	0.314	0.194	0.048	0.171
0.002	500	0.37	1.08	0.709	0.314	0.194	0.048	0.171
0.002	500	0.47	1.18	0.697	0.309	0.191	0.047	0.169
0.002	500	0.57	1.28	0.697	0.309	0.191	0.047	0.169
0.002	500	0.77	1.48	0.628	0.278	0.171	0.042	0.152
0.002	500	0.87	1.58	0.581	0.257	0.159	0.039	0.140
0.002	500	0.97	1.68	0.570	0.252	0.156	0.038	0.138
0.002	500	1.04	1.75	0.465	0.206	0.127	0.031	0.112
0.002	500	1.14	1.85	0.232	0.103	0.064	0.016	0.056
0.002	500	1.20	1.91	0.116	0.051	0.032	0.008	0.028
0.002	500	1.24	1.95	0.000	0.000	0.000	0.000	0.000

Table 2-10: Combinations of sea level and wave height at selected ARTEMIS output sites with specified joint annual exceedance probabilities, under a 100 year climate change scenario. Sea levels in the third column are referred to the projected mean sea level, which is assumed to be 1.0 m above present mean sea level. In column 4, these offsets are added in to give levels relative to WVD-53.

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.632	1	0.00	1.21	0.101	0.058	0.038	0.013	0.044
0.632	1	0.04	1.25	0.101	0.058	0.038	0.013	0.044
0.632	1	0.34	1.55	0.099	0.057	0.037	0.013	0.043
0.632	1	0.45	1.66	0.097	0.056	0.036	0.013	0.042
0.632	1	0.54	1.75	0.093	0.053	0.035	0.012	0.040
0.632	1	0.74	1.95	0.074	0.042	0.027	0.010	0.032
0.632	1	0.84	2.05	0.053	0.030	0.020	0.007	0.023
0.632	1	0.88	2.09	0.039	0.022	0.014	0.005	0.017
0.632	1	0.92	2.13	0.019	0.011	0.007	0.003	0.008
0.632	1	0.94	2.15	0.006	0.003	0.002	0.001	0.003
0.632	1	0.94	2.15	0.000	0.000	0.000	0.000	0.000
0.095	10	0.00	1.21	0.253	0.142	0.089	0.028	0.096
0.095	10	0.03	1.24	0.253	0.142	0.089	0.028	0.096

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.095	10	0.33	1.54	0.249	0.140	0.088	0.028	0.094
0.095	10	0.53	1.74	0.236	0.133	0.083	0.026	0.089
0.095	10	0.73	1.94	0.211	0.118	0.074	0.024	0.080
0.095	10	0.73	1.94	0.211	0.118	0.074	0.024	0.080
0.095	10	0.83	2.04	0.186	0.104	0.066	0.021	0.070
0.095	10	0.93	2.14	0.139	0.078	0.049	0.016	0.053
0.095	10	1.01	2.22	0.084	0.047	0.030	0.009	0.032
0.095	10	1.03	2.24	0.042	0.024	0.015	0.005	0.016
0.095	10	1.03	2.24	0.038	0.021	0.013	0.004	0.014
0.095	10	1.04	2.25	0.000	0.000	0.000	0.000	0.000
0.02	50	0.00	1.21	0.411	0.213	0.132	0.038	0.132
0.02	50	0.03	1.24	0.411	0.213	0.132	0.038	0.132
0.02	50	0.33	1.54	0.411	0.213	0.132	0.038	0.132
0.02	50	0.53	1.74	0.405	0.209	0.130	0.037	0.130
0.02	50	0.73	1.94	0.372	0.192	0.120	0.034	0.119
0.02	50	0.83	2.04	0.346	0.179	0.111	0.032	0.111
0.02	50	0.86	2.07	0.327	0.169	0.105	0.030	0.105
0.02	50	0.93	2.14	0.294	0.152	0.095	0.027	0.094
0.02	50	1.03	2.24	0.196	0.101	0.063	0.018	0.063
0.02	50	1.08	2.29	0.131	0.067	0.042	0.012	0.042
0.02	50	1.10	2.31	0.065	0.034	0.021	0.006	0.021
0.02	50	1.11	2.32	0.000	0.000	0.000	0.000	0.000
0.01	100	0.00	1.21	0.499	0.247	0.153	0.042	0.148
0.01	100	0.03	1.24	0.499	0.247	0.153	0.042	0.148
0.01	100	0.34	1.54	0.499	0.247	0.153	0.042	0.148
0.01	100	0.54	1.74	0.491	0.243	0.151	0.041	0.145
0.01	100	0.74	1.94	0.460	0.228	0.141	0.039	0.136
0.01	100	0.84	2.04	0.452	0.224	0.139	0.038	0.134
0.01	100	0.91	2.11	0.390	0.193	0.120	0.033	0.115
0.01	100	0.94	2.14	0.367	0.181	0.113	0.031	0.108
0.01	100	1.04	2.24	0.296	0.147	0.091	0.025	0.088
0.01	100	1.12	2.32	0.156	0.077	0.048	0.013	0.046
0.01	100	1.15	2.35	0.078	0.039	0.024	0.007	0.023
0.01	100	1.15	2.35	0.000	0.000	0.000	0.000	0.000
0.005	200	0.00	1.21	0.603	0.285	0.176	0.046	0.164
0.005	200	0.04	1.25	0.603	0.285	0.176	0.046	0.164
0.005	200	0.34	1.55	0.603	0.285	0.176	0.046	0.164
0.005	200	0.54	1.75	0.594	0.281	0.174	0.045	0.161
0.005	200	0.74	1.95	0.566	0.268	0.166	0.043	0.154

AEP	ARI (years)	sea level (m) - MSL	sea level (m) – WVD-53	wave height (m) at site 14	wave height (m) at site 15	wave height (m) at site 16	wave height (m) at site 17	wave height (m) at site 18
0.005	200	0.84	2.05	0.566	0.268	0.166	0.043	0.154
0.005	200	0.94	2.15	0.464	0.219	0.136	0.035	0.126
0.005	200	0.94	2.15	0.464	0.219	0.136	0.035	0.126
0.005	200	1.04	2.25	0.390	0.184	0.114	0.030	0.106
0.005	200	1.16	2.37	0.186	0.088	0.054	0.014	0.050
0.005	200	1.18	2.39	0.093	0.044	0.027	0.007	0.025
0.005	200	1.18	2.39	0.000	0.000	0.000	0.000	0.000
0.002	500	0.00	1.21	0.779	0.345	0.213	0.052	0.188
0.002	500	0.08	1.29	0.779	0.345	0.213	0.052	0.188
0.002	500	0.38	1.59	0.779	0.345	0.213	0.052	0.188
0.002	500	0.58	1.79	0.779	0.345	0.213	0.052	0.188
0.002	500	0.78	1.99	0.732	0.324	0.200	0.049	0.177
0.002	500	0.88	2.09	0.732	0.324	0.200	0.049	0.177
0.002	500	0.98	2.19	0.697	0.309	0.191	0.047	0.169
0.002	500	1.02	2.23	0.581	0.257	0.159	0.039	0.140
0.002	500	1.08	2.29	0.558	0.247	0.152	0.037	0.135
0.002	500	1.23	2.44	0.232	0.103	0.064	0.016	0.056
0.002	500	1.24	2.45	0.116	0.051	0.032	0.008	0.028
0.002	500	1.24	2.45	0.000	0.000	0.000	0.000	0.000

2.8 Estimation of combined sea level plus runup

The joint exceedance probability tables computed above provide a set of combinations of sea level and wave conditions that might be expected to be exceeded with a given probability each year. Each of these combinations may have a different level of severity depending on the hazard being considered (e.g. wave overtopping, damage by waves). As an indication, we have considered a simple estimate of the additional effect of wave runup on a constant slope, to be added to the still water sea level.

To do so we have applied empirical runup formulae from the EuroTop manual (Pullen, Allsop et al. 2007). Specifically, we estimate the runup $R_{u2\%}$ expected to be exceeded by 2% of waves in an event where the significant wave height is H_{m0} as:

$$R_{u2\%} / H_{m0} = \min\begin{cases} C_1 \gamma_b \gamma_f \gamma_\beta \xi \\ \gamma_b \gamma_f \left(C_2 - C_3 / \sqrt{\xi}\right) \end{cases} \tag{10}$$

This depends on a breaker parameter

$$\xi = \frac{\tan\alpha}{\sqrt{H_{m0} / L_0}} \tag{11}$$

where $\tan\alpha$ is the seabed slope, L_0 is the deepwater mean wavelength

$$L_0 = \frac{g T_m^2}{2\pi} \tag{12}$$

This requires a mean wave period T_m, which we took as 3.4 seconds, derived from the mean value of peak period over the events simulated. After inspection of a set of nearshore bathymetry transects through the Queens Wharf area, a bottom slope of $\tan\alpha = 0.5$ was applied throughout. The empirical constants were taken as $C_1 = 1.5$, $C_2 = 4.0$, $C_3 = 1.5$, while any effects of a berm and oblique wave incidence were ignored by taking $\gamma_b = 1.0$ and $\gamma_\beta = 1.0$, respectively. The roughness factor γ_f was set to 0.5, typical of a rocky bottom (a value of 1.0 would apply for a perfectly smooth, solid bed).

This allowed us to estimate the runup associated with each value of significant wave height in the joint exceedance tables. The results, adding the estimated runup to the sea level, are presented for present day climate conditions in

Table 2-11, for 50 year projected climate conditions in
Table 2-12, and for a 100 year projection in

Table 2-13. We note that, given the sheltered location, the highest total levels are predominant associated with high (still water) sea levels, rather than larger waves on top of lower still water levels. It should be stressed that the simple runup estimate made here can be indicative of the total hazard associated with a given combination of waves and sea level, but does not replace a more complete engineering analysis, should that be required for design purposes.

Table 2-11: Estimated values of combined sea level plus runup, in metres above WVD-53 at selected ARTEMIS output sites with specified joint exceedance probabilities, under present climate conditions. Derived from the joint exceedance values in Table 2-8.

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.632	1	0.21	0.35	0.29	0.26	0.23	0.27
0.632	1	0.34	0.48	0.42	0.39	0.36	0.40
0.632	1	0.54	0.68	0.62	0.59	0.56	0.60
0.632	1	0.74	0.87	0.81	0.79	0.76	0.80
0.632	1	0.84	0.96	0.91	0.88	0.86	0.89
0.632	1	0.94	1.04	1.00	0.98	0.95	0.98
0.632	1	0.94	1.04	1.00	0.98	0.95	0.98
0.632	1	1.04	1.11	1.08	1.07	1.05	1.07
0.632	1	1.11	1.14	1.13	1.12	1.11	1.12
0.632	1	1.13	1.15	1.14	1.14	1.13	1.14
0.632	1	1.14	1.15	1.14	1.14	1.14	1.14
0.632	1	1.15	1.15	1.15	1.15	1.15	1.15
0.095	10	0.21	0.54	0.40	0.33	0.25	0.34
0.095	10	0.34	0.68	0.54	0.47	0.38	0.48
0.095	10	0.54	0.87	0.73	0.66	0.58	0.67
0.095	10	0.74	1.06	0.92	0.86	0.78	0.87
0.095	10	0.84	1.14	1.02	0.95	0.88	0.96
0.095	10	0.94	1.22	1.10	1.05	0.98	1.05
0.095	10	1.04	1.29	1.19	1.13	1.07	1.14
0.632	10	1.10	1.32	1.23	1.18	1.13	1.19
0.095	10	1.14	1.33	1.25	1.21	1.16	1.22
0.095	10	1.23	1.31	1.28	1.26	1.24	1.26

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.095	10	1.24	1.28	1.26	1.25	1.25	1.26
0.632	10	1.25	1.25	1.25	1.25	1.25	1.25
0.02	50	0.21	0.74	0.49	0.39	0.26	0.39
0.02	50	0.33	0.87	0.62	0.51	0.39	0.51
0.02	50	0.53	1.07	0.82	0.71	0.59	0.71
0.02	50	0.61	1.14	0.89	0.79	0.66	0.79
0.02	50	0.73	1.25	1.01	0.91	0.78	0.91
0.02	50	0.83	1.33	1.10	1.00	0.88	1.00
0.02	50	0.93	1.40	1.18	1.09	0.98	1.09
0.02	50	1.03	1.47	1.26	1.18	1.08	1.18
0.02	50	1.13	1.50	1.33	1.25	1.17	1.25
0.02	50	1.19	1.52	1.36	1.30	1.22	1.30
0.02	50	1.29	1.40	1.35	1.33	1.30	1.33
0.02	50	1.30	1.36	1.33	1.32	1.31	1.32
0.02	50	1.32	1.32	1.32	1.32	1.32	1.32
0.01	100	0.21	0.85	0.54	0.42	0.27	0.41
0.01	100	0.34	0.99	0.68	0.55	0.40	0.55
0.01	100	0.54	1.19	0.88	0.75	0.60	0.75
0.01	100	0.71	1.33	1.03	0.92	0.77	0.91
0.01	100	0.74	1.36	1.06	0.95	0.80	0.94
0.01	100	0.84	1.45	1.16	1.04	0.90	1.04
0.01	100	0.94	1.52	1.24	1.13	1.00	1.12
0.01	100	1.04	1.59	1.33	1.22	1.09	1.22
0.01	100	1.14	1.61	1.38	1.30	1.19	1.29
0.01	100	1.24	1.63	1.44	1.37	1.28	1.36
0.01	100	1.34	1.48	1.41	1.39	1.36	1.38
0.01	100	1.34	1.41	1.38	1.36	1.35	1.36
0.01	100	1.35	1.35	1.35	1.35	1.35	1.35
0.005	200	0.21	0.99	0.60	0.46	0.28	0.44
0.005	200	0.35	1.13	0.74	0.60	0.42	0.58
0.005	200	0.55	1.31	0.92	0.79	0.61	0.77
0.005	200	0.75	1.49	1.12	0.98	0.81	0.97
0.005	200	0.84	1.57	1.20	1.07	0.90	1.05
0.005	200	0.85	1.58	1.21	1.08	0.91	1.06
0.005	200	0.95	1.65	1.30	1.17	1.01	1.15
0.005	200	1.05	1.71	1.38	1.26	1.11	1.24
0.005	200	1.15	1.78	1.46	1.35	1.20	1.33
0.005	200	1.27	1.72	1.49	1.41	1.31	1.40
0.005	200	1.37	1.45	1.41	1.39	1.38	1.39

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.005	200	1.37	1.53	1.45	1.42	1.38	1.41
0.005	200	1.39	1.39	1.39	1.39	1.39	1.39
0.002	500	0.21	1.19	0.67	0.50	0.28	0.47
0.002	500	0.38	1.37	0.84	0.67	0.46	0.64
0.002	500	0.58	1.57	1.04	0.87	0.66	0.84
0.002	500	0.78	1.73	1.23	1.06	0.85	1.03
0.002	500	0.88	1.80	1.31	1.15	0.95	1.12
0.002	500	0.92	1.82	1.34	1.19	0.99	1.16
0.002	500	0.98	1.88	1.40	1.25	1.05	1.22
0.002	500	1.08	1.98	1.50	1.35	1.15	1.32
0.002	500	1.18	2.00	1.56	1.42	1.24	1.40
0.002	500	1.35	1.91	1.61	1.51	1.39	1.50
0.002	500	1.45	1.45	1.45	1.45	1.45	1.45

Table 2-12: Estimated values of combined sea level plus runup, in metres above WVD-53 at selected ARTEMIS output sites with specified joint exceedance probabilities under a 50 year climate change scenario, which includes a 0.5 m sea level rise. Derived from the joint exceedance values in

Table 2-9.

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.632	1	0.71	0.86	0.80	0.77	0.73	0.78
0.632	1	0.89	1.05	0.98	0.95	0.91	0.96
0.632	1	1.09	1.24	1.18	1.15	1.11	1.16
0.632	1	1.29	1.43	1.37	1.34	1.31	1.35
0.632	1	1.34	1.47	1.42	1.39	1.36	1.40
0.632	1	1.49	1.59	1.55	1.53	1.50	1.54
0.632	1	1.58	1.65	1.62	1.60	1.59	1.61
0.632	1	1.59	1.65	1.63	1.61	1.60	1.62
0.632	1	1.62	1.65	1.64	1.63	1.62	1.63
0.632	1	1.65	1.65	1.65	1.65	1.65	1.65
0.095	10	0.71	1.08	0.92	0.85	0.75	0.86
0.095	10	0.88	1.26	1.10	1.02	0.93	1.03
0.095	10	1.08	1.45	1.29	1.22	1.13	1.23
0.095	10	1.28	1.63	1.48	1.41	1.33	1.42
0.095	10	1.48	1.78	1.66	1.59	1.52	1.60
0.095	10	1.53	1.81	1.69	1.64	1.57	1.64
0.095	10	1.58	1.83	1.73	1.67	1.61	1.68
0.095	10	1.68	1.86	1.79	1.75	1.70	1.75
0.095	10	1.71	1.86	1.79	1.77	1.73	1.77
0.095	10	1.73	1.81	1.78	1.76	1.74	1.76

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.095	10	1.75	1.75	1.75	1.75	1.75	1.75
0.02	50	0.71	1.31	1.03	0.91	0.77	0.91
0.02	50	0.88	1.49	1.21	1.09	0.94	1.09
0.02	50	1.08	1.68	1.40	1.28	1.14	1.28
0.02	50	1.28	1.86	1.59	1.48	1.34	1.48
0.02	50	1.48	1.99	1.75	1.65	1.53	1.65
0.02	50	1.58	2.05	1.83	1.74	1.63	1.74
0.02	50	1.63	2.06	1.86	1.78	1.67	1.78
0.02	50	1.68	2.07	1.89	1.81	1.72	1.81
0.02	50	1.79	2.01	1.91	1.87	1.81	1.87
0.02	50	1.81	1.92	1.87	1.85	1.82	1.85
0.02	50	1.82	1.82	1.82	1.82	1.82	1.82
0.01	100	0.71	1.43	1.08	0.95	0.78	0.94
0.01	100	0.88	1.61	1.26	1.12	0.95	1.11
0.01	100	1.08	1.81	1.46	1.32	1.15	1.31
0.01	100	1.28	1.99	1.65	1.51	1.35	1.50
0.01	100	1.48	2.10	1.80	1.69	1.54	1.68
0.01	100	1.58	2.18	1.89	1.78	1.64	1.77
0.01	100	1.68	2.19	1.94	1.85	1.73	1.84
0.01	100	1.68	2.19	1.94	1.85	1.73	1.84
0.01	100	1.81	2.07	1.95	1.90	1.84	1.89
0.01	100	1.84	1.98	1.91	1.89	1.86	1.88
0.01	100	1.85	1.85	1.85	1.85	1.85	1.85
0.005	200	0.71	1.57	1.14	0.98	0.78	0.96
0.005	200	0.90	1.77	1.33	1.17	0.97	1.15
0.005	200	1.10	1.97	1.53	1.37	1.17	1.35
0.005	200	1.30	2.15	1.72	1.57	1.37	1.55
0.005	200	1.50	2.26	1.87	1.74	1.56	1.72
0.005	200	1.60	2.32	1.95	1.82	1.66	1.81
0.005	200	1.70	2.36	2.03	1.91	1.76	1.89
0.005	200	1.74	2.33	2.03	1.92	1.79	1.91
0.005	200	1.84	2.15	1.99	1.93	1.86	1.93
0.005	200	1.88	2.04	1.96	1.93	1.89	1.92
0.005	200	1.89	1.89	1.89	1.89	1.89	1.89
0.002	500	0.71	1.79	1.22	1.03	0.79	0.99
0.002	500	0.88	1.97	1.39	1.20	0.97	1.17
0.002	500	1.08	2.17	1.59	1.40	1.17	1.37
0.002	500	1.18	2.25	1.68	1.50	1.26	1.46
0.002	500	1.28	2.35	1.78	1.60	1.36	1.56

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.002	500	1.48	2.45	1.93	1.77	1.56	1.74
0.002	500	1.58	2.48	2.00	1.85	1.65	1.82
0.002	500	1.68	2.57	2.09	1.94	1.75	1.91
0.002	500	1.75	2.48	2.09	1.97	1.81	1.94
0.002	500	1.85	2.23	2.03	1.96	1.88	1.95
0.002	500	1.91	2.11	2.00	1.97	1.93	1.96
0.002	500	1.95	1.95	1.95	1.95	1.95	1.95
0.002	500	1.35	1.46	1.42	1.39	1.37	1.41
0.002	500	1.45	1.45	1.45	1.45	1.45	1.45

Table 2-13: Estimated values of combined sea level plus runup, in metres above WVD-53 at selected ARTEMIS output sites with specified joint exceedance probabilities, under climate conditions expected for a 100 year climate change scenario, which includes a 1.0 m sea level rise. Derived from the joint exceedance values in Table 2-10.

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.632	1	1.21	1.38	1.31	1.28	1.23	1.29
0.632	1	1.25	1.42	1.35	1.32	1.27	1.33
0.632	1	1.55	1.72	1.65	1.61	1.57	1.62
0.632	1	1.66	1.83	1.76	1.72	1.68	1.73
0.632	1	1.75	1.91	1.84	1.81	1.77	1.82
0.632	1	1.95	2.08	2.02	2.00	1.97	2.01
0.632	1	2.05	2.14	2.10	2.09	2.06	2.09
0.632	1	2.09	2.16	2.13	2.11	2.10	2.12
0.632	1	2.13	2.16	2.15	2.14	2.13	2.14
0.632	1	2.15	2.16	2.15	2.15	2.15	2.15
0.632	1	2.15	2.15	2.15	2.15	2.15	2.15
0.095	10	1.21	1.62	1.45	1.36	1.26	1.37
0.095	10	1.24	1.66	1.48	1.39	1.29	1.41
0.095	10	1.54	1.95	1.78	1.69	1.59	1.70
0.095	10	1.74	2.13	1.97	1.89	1.79	1.89
0.095	10	1.94	2.29	2.14	2.07	1.99	2.08
0.095	10	1.94	2.29	2.14	2.07	1.99	2.08
0.095	10	2.04	2.35	2.22	2.16	2.08	2.16
0.095	10	2.14	2.38	2.28	2.23	2.17	2.23
0.095	10	2.22	2.37	2.30	2.28	2.24	2.28
0.095	10	2.24	2.32	2.29	2.27	2.25	2.27
0.095	10	2.24	2.31	2.28	2.27	2.25	2.27
0.095	10	2.25	2.25	2.25	2.25	2.25	2.25
0.02	50	1.21	1.86	1.56	1.43	1.28	1.43

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.02	50	1.24	1.89	1.59	1.46	1.31	1.46
0.02	50	1.54	2.19	1.89	1.76	1.61	1.76
0.02	50	1.74	2.38	2.09	1.96	1.81	1.96
0.02	50	1.94	2.54	2.26	2.14	2.00	2.14
0.02	50	2.04	2.60	2.34	2.23	2.10	2.23
0.02	50	2.07	2.60	2.35	2.25	2.12	2.25
0.02	50	2.14	2.62	2.40	2.30	2.19	2.30
0.02	50	2.24	2.57	2.41	2.35	2.27	2.35
0.02	50	2.29	2.51	2.41	2.37	2.31	2.37
0.02	50	2.31	2.42	2.37	2.35	2.32	2.35
0.02	50	2.32	2.32	2.32	2.32	2.32	2.32
0.01	100	1.21	1.99	1.61	1.46	1.28	1.46
0.01	100	1.24	2.03	1.65	1.50	1.32	1.49
0.01	100	1.54	2.33	1.95	1.80	1.62	1.79
0.01	100	1.74	2.51	2.14	2.00	1.82	1.99
0.01	100	1.94	2.67	2.32	2.18	2.01	2.17
0.01	100	2.04	2.76	2.41	2.28	2.11	2.27
0.01	100	2.11	2.73	2.43	2.32	2.17	2.31
0.01	100	2.14	2.73	2.44	2.34	2.20	2.33
0.01	100	2.24	2.72	2.49	2.40	2.29	2.39
0.01	100	2.32	2.58	2.46	2.41	2.35	2.40
0.01	100	2.35	2.49	2.42	2.40	2.37	2.39
0.01	100	2.35	2.35	2.35	2.35	2.35	2.35
0.005	200	1.21	2.14	1.67	1.50	1.29	1.48
0.005	200	1.25	2.18	1.71	1.54	1.33	1.52
0.005	200	1.55	2.48	2.01	1.84	1.63	1.82
0.005	200	1.75	2.67	2.21	2.04	1.83	2.02
0.005	200	1.95	2.83	2.39	2.23	2.02	2.21
0.005	200	2.05	2.93	2.49	2.33	2.12	2.31
0.005	200	2.15	2.88	2.51	2.38	2.21	2.36
0.005	200	2.15	2.88	2.51	2.38	2.21	2.36
0.005	200	2.25	2.87	2.55	2.44	2.30	2.43
0.005	200	2.37	2.68	2.52	2.46	2.39	2.46
0.005	200	2.39	2.55	2.47	2.44	2.40	2.43
0.005	200	2.39	2.39	2.39	2.39	2.39	2.39
0.002	500	1.21	2.39	1.76	1.56	1.30	1.52
0.002	500	1.29	2.47	1.85	1.64	1.38	1.60
0.002	500	1.59	2.77	2.15	1.94	1.68	1.90
0.002	500	1.79	2.97	2.35	2.14	1.88	2.10

AEP	ARI (years)	sea level (m) – WVD-53	SL + runup (m) site 14	SL + runup (m) site 15	SL + runup (m) site 16	SL + runup (m) site 17	SL + runup (m) site 18
0.002	500	1.99	3.11	2.51	2.32	2.08	2.29
0.002	500	2.09	3.21	2.61	2.42	2.18	2.39
0.002	500	2.19	3.26	2.69	2.51	2.27	2.47
0.002	500	2.23	3.13	2.65	2.50	2.30	2.47
0.002	500	2.29	3.16	2.70	2.55	2.36	2.52
0.002	500	2.44	2.82	2.62	2.55	2.47	2.54
0.002	500	2.45	2.65	2.54	2.51	2.47	2.50
0.002	500	2.45	2.45	2.45	2.45	2.45	2.45
0.002	500	1.18	1.41	1.32	1.28	1.22	1.28
0.002	500	1.35	1.46	1.42	1.39	1.37	1.41
0.002	500	1.45	1.45	1.45	1.45	1.45	1.45

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